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CENTRALIZED VS. DECENTRALIZED ENERGY SYSTEMS: DIVERGING OR PARALLEL ROADS?

A REPORT

PREPARED FOR THE USE OF THE

SUBCOMMITTEE ON ENERGY AND POWER,
COMMITTEE ON
INTERSTATE AND FOREIGN COMMERCE
UNITED STATES HOUSE OF REPRESENTATIVES

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LETTER OF TRANSMITTAL

Congress of the United States,
House of Representatives,
Subcommittee on Energy and Power,
Committee on Interstate and Foreign Commerce,
Washington, D.C., May 22, 1979.

Hon. Harley O. Staggers,
Chairman, Committee on Interstate and Foreign Commerce, 2125 Rayburn House Office Building, U.S. House of Representatives, Washington, D.C.

Dear Mr. Chairman: Attached is a study performed by the Congressional Research Service for the Subcommittee on Energy and Power entitled "Centralized vs. Decentralized Energy Systems: Diverging or Parallel Roads?" I believe it would be useful if this study were to be published as a committee print.

The study, done under the supervision of Mr. Carl Behrens, Analyst in Environmental Policy, consists of a research paper on the general subject by Mr. Behrens and a collection of papers on some of the subtopics by various authors. The study discusses the merits of providing energy for our national needs with and without central electric power generation and what the effects of each of these two paths may be.

I believe that all Members of the House will find the study to be of interest.

Sincerely,

John D. Dingell, *Chairman.*

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LETTER OF SUBMITTAL

The Library of Congress,
Congressional Research Service,
Washington, D.C., May 16, 1979.

Hon. John D. Dingell,
Chairman, Subcommittee on Energy and Power,
Committee on Interstate and Foreign Commerce,
House of Representatives,
Washington, D.C.

Dear Chairman Dingell: I am pleased to submit to you a report entitled "Centralized Vs. Decentralized Energy Systems: Diverging or Parallel Roads?" which was prepared by the Congressional Research Service pursuant to your request.

The report consists of an analytical study of the pros and cons of decentralization, entitled "Decentralizing Electric Power Generation: Technologies, Goals and Consequences," followed by a number of articles dealing with various aspects of electric power and decentralization. The CRS study describes the technologies that may be considered decentralized, discusses the goals and value measures that are involved in pursuit of decentralization (and of energy policy in general), and analyzes the present state of the electric utility industry and the effects that decentralization could have on the industry.

The readings are divided into several topics, including general energy policy, the utility industry, solar energy, and cogeneration and waste heat utilization.

The CRS study was prepared by Dr. Carl E. Behrens, Analyst in the Environment and Natural Resources Policy Division, with substantial contributions by Mr. Alvin Kaufman, Senior Specialist in Mineral and Regulatory Economics, and Ms. Susan J. Bodilly, Research Assistant. The readings were selected and are introduced by Dr. Behrens. We hope the report will be useful to you and your committee in determining energy policies that will affect the future economic and environmental well-being of the Nation.

Sincerely,

T. W. Novotny,
(for Gilbert Gude, Director).

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CENTRALIZED VS. DECENTRALIZED ENERGY SYSTEMS: DIVERGING OR PARALLEL ROADS?

Decentralizing Electric Power Generation: Technologies; Goals and Consequences

(By Carl E. Behrens, Alvin Kaufman, and Susan Bodilly)

INTRODUCTION*

The electric power industry is going through a period of revoluntionary change. From a period of rapid growth, declining costs, increased centralization and larger generating and transmission units, it has moved into an era of uncertain growth, sharply higher costs, capital scarcities and grave difficulties in siting and constructing new facilities. In addition, it is at the focal point of continuing debate on the philosophy of energy use in the future. That debate includes specific questions such as the means of reducing dependence on foreign oil, or the role of nuclear power, but it also extends to questions of economic growth, of social organization, and reliance on technological solutions.

The philosophical questions cited above are potentially much more significant to the future of the electric utility industry than the mundane facts of finance and construction. Depending on the outcome of the energy policy debate, a central electric power system, linked with effective waste-heat utilization and cogeneration technology, could conceivably overcome its short-term problems and become dominant in energy production in all sectors of the economy, far in excess of its present role, which is essential but limited. On the other hand, again as a result of the policies adopted to deal with energy questions,the present semi-unified electric system might be reduced to a minor disaggregated source of high quality energy for uses where it is irreplaceable, as in control technology and electronics, or where it is demonstrably superior, as in lighting and mechanical power.

Between these two extremes lies a more conventional projection of the energy future. It is that electricity will continue to be significant and competitive, but that most energy will come from other sources: conventional fossil fuels, unconventional sources of liquid and gaseous hydrocarbons, and growing amounts of renewable energy resources.

This conventional view has two groups of supporters. One group considers that major changes in the energy supply system will be necessary to deal with declining world resources of oil and natural gas, but that a number of new energy sources, combined with conservation measures and more efficient consumption practices, can be developed so as to achieve the transition. The other group suggests that liquid and gaseous hydrocarbons will have a more enduring role than many current views of the post-embargo energy crisis are willing to grant them, reducing the need to deploy new technologies beyond the level stimulated by the normal competitive market.

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* This section, and the following three sections, were prepared by Carl E. Behrens.

However, the conventional view, in both varieties, is strongly challenged, both by those who see a minimal role for electricity in the future, and by those who predict a dominant role for it. The first school of thought is most prominently expressed by Amory Lovins,[1] while the second is represented by many utility contributors to the energy debate. Both generally agree that a prompt transition from oil and natural gas is necessary. However, Lovins advocates developing renewable technologies, principally solar power for space conditioning and process heat and biomass for transportation, and rejects "hard" technologies, of which central electric power, particularly nuclear power, is the prime example.

A significant feature of Lovin's model is his insistence that the hard and soft energy paths are incompatible To a great extent, this position is based on his belief that use of nuclear power will lead to proliferation of nuclear weapons.[2]

The second group is skeptical of the economic competitiveness of soft technologies and unconventional sources of hydrocarbons compared with central electric power generation, again featuring nuclear power.[3] For this group, nuclear electricity could play a major role in substituting for oil or gas in industry, in the residential and commercial sectors, and even in the transportation sector when electric vehicles are developed

Thus the future role of central electricity is the subject of considerable debate, the outcome of which is not clear at present. Within this broad question the various decentralized technologies have a crucial but complex role. Part of that complexity derives from difficulties in defining decentralized technology, and determining whether a particular technology fits that definition. Another variable is the motivation for seeking decentralization; some goals would be met by one type of technology, other goals by other types.

Both of these questions are dealt with later in this study. First, however, it may be useful to describe the various technologies that might, under one definition or another, be considered decentralized. The following pages are devoted to these topics. A description of the present state of the electric power industry follows, with a concluding section on the future of that industry in the light of these factors.

DECENTRALIZED TECHNOLOGIES

A large number of existing or developing technologies may be defined as "decentralized"—or at least "decentralizing", in the sense that they take the place of central generating facilities. Because some are more applicable to one energy-consuming sector than another, they are described below in the context of the household/commercial, industrial, transportation and electric generating sectors.

---

[1] Lovins, Amory B. Soft Energy Paths: Toward a Durable Peace. Cambridge: Ballinger Publishing Co 1977.

[2] "We must choose between the soft and hard energy paths before failure to stop nuclear proliferation has foreclosed both," he says in a chapter titled "Rebottling the Nuclear Genie" (ibid., p. 171), and adds: "[T]he nuclear choice lies near the center of the energy problem." Although the nuclear factor is the most clear-cut reason cited for the incompatibility of the hard and soft paths, Lovins also indicates that the two are in competition for resources, time, and effort: they are "logistically competitive, institutionally incompatible and culturally antithetical," he says (ibid., p. 49).

[3] Starr, Chauncey. The Electricity Future: What Can You Believe? Aware, November, 1978, pp. 2–5.

Household/commercial sector

In this sector, the major energy demands are for space conditioning and hot water, mechanical energy for appliances, lights, and electronics. Space conditioning and hot water are supplied by oil, natural gas, electricity and, to a very small extent, coal. The other energy uses are predominantly supplied by electricity. For all uses in this sector, gas supplied 40% of the energy consumed during 1978, petroleum supplied 37%, electricity 21% and coal a little more than 1%.[4]

Among decentralized technologies, conservation, in the form of insulation and similar technologies, is the most accessible and immediately available for existing structures. Its applicability is probably widespread but limited in effect. Various programs, some of them carried out through electric utilities, should yield more information soon on the potential of this technology. For new buildings the concept of conservation can be extended to include passive solar design, by means of which a large proportion of heating and cooling needs, or even in some cases all of them, may be met.

Active solar heating is also a major near-term dispersed technology, and probably the most significant decentralized competitor to electric power in the household/commercial sector. Although technology exists to supply all heating needs by active solar heat in many locations, economic factors appear at present to limit most installations so that they require some kind of backup heat, either electricity or oil or gas.

Decentralized technologies for providing electricity include cogeneration units, which also supply heat for residential or commercial complexes. They also include fuel cells, which can be built in small units and promise higher efficiencies than electric steam generation technology, as well as the possibility of cogeneration applications. Both these systems use oil or natural gas at present, but presumably could run on bio-gas or other substitute fuels if they were available.

Some residential/commercial cogeneration facilities are operating at present, but fuel uncertainties appear to be inhibiting their expansion. Fuel cells are on the verge of commercial application as part of the central electric grid, where they could be used as efficient and environmentally improved facilities for load-following generators in the 5–25 megawatt (MWe) range, but the technology is also being pursued at the level of 25–200 kilowatts (kWe) for use in the residential/commercial sector, perhaps as part of the gas utility distribution system.[5]

Other decentralized electric generating technologies include windmills, which would find most applications in rural areas, and photovoltaic cells, which hold great promise as dispersed technology but are limited by cost at present. Both these technologies would require either some form of storage or connection with a backup electric system.

District heating is an ambitious concept which would require large capital investment but which would, according to some observers, represent a practical use for the large amount of waste heat from electric power plants. One problem with this technology is that hot water from power plant condensers would require augmentation of heat to be practical for district heating. It is possible, however, that the augmenting heat could come from other dispersed technologies, such as solar collectors.

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[4] U.S. Department of Energy. Monthly Energy Review. (DOE/EIA–0035/4(79)). April 1979, p. 24.

[5] Clean Power for the Cities. EPRI Journal. November 1978, pp. 6–12

Industrial sector

The major energy uses in the industrial sector are for process heat and mechanical energy, with space conditioning, lights and electronics playing a smaller role. Gas, oil, coal and electricity are sources of process heat; most mechanical energy is supplied by electricity. Overall energy consumption in this sector during 1978 was 39% gas, 32% petroleum, 16% coal, and 13% electricity.[6]

The major prospect for decentralizing electric power generation in this sector is the development of cogeneration facilities located at industrial use sites. Most concepts of industrial cogeneration include connection with a central utility both for backup power and as a customer for surplus electricity produced by the cogeneration facility. The National Energy Act directs the Federal Energy Regulation Commission to develop regulations that will make this combination of decentralized technology with the central grid more practical for the industrial user.

Waste hear utilization, in contrast to cogeneration, consists of using the discharge heat from power plants rather than producing both electricity and heat for on-site use. For most uses, hot water from electric plants would need augmentation.

Small hydro systems, if conveniently located, may be used as completely independent facilities. It seems likely, however, as with cogeneration facilities, that connection with a central grid may be advantageous, to supply backup power in case of unusual requirements, and to serve as a market for surplus power produced by the unit when that is available.

Other decentralized technologies that may be used in the industrial sector include on-site gasification or liquefaction of coal, or other synthetic liquid or gaseous fuels; solar process heat, both for agriculture and other industries, and wood and waste combustion.

Transportation sector

Since electricity contributes only a very small fraction of energy to the transportation sector, any new technology in this area would be "decentralized" only in the sense that in substituting for oil, it would forestall the increased use of electricity, for example in electric vehicles or expanded electric rail use. Methanol from biomass is mentioned by Lovins as the prime "soft" energy alternative to gasoline; other alternatives are synthetic liquids from coal or other sources.

Electric power sector

Several technologies have been suggested for smaller unit electric energy facilities, including medium-sized coal units and fuel cells for location in near-use locations. It is argued that these facilities would make it more likely that small, locally controlled utilities could compete with the giant organizations fostered by massive base-load coal and nuclear units. Other decentralized technologies such as windmills, photovoltaic systems, and small hydroelectric facilities, also could fulfill this decentralizing function.

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[6] Monthly Energy Review ,op. cit., p. 25.

TAXONOMY OF DECENTRALIZATION

The technologies or energy sources described above may or may not be considered decentralized, depending on how that term is defined. A variety of characteristics may be used to determine whether a technology is decentralized or not.

Point of conversion or production

One measure of decentralization may be whether the energy form is produced (or converted from another energy form) at the point of end use, or at a distant facility.

In the case of electric energy, this distinction seems fairly clear: electricity produced by a nuclear plant and distributed by a utility through a central grid to the consumer is centralized, and a photovoltaic device on a housetop producing electricity used in that house is decentralized. There is a gradation in this variable, however, depending on the size of the generating unit, and the size of the market it serves. A fuel cell distributing electricity to a small community or a group of buildings could be considered more decentralized than the same unit feeding directly into a central grid, but even in the latter case a small fuel cell facility located near the point of use would be less centralized (by this definition) than a large plant located miles out of town.

The picture becomes less clear in the case of other energy sources. Solar heating would appear to be definitely decentralized, although once again gradations are observable in the number of units served. However, if the solar system is combined with other energy sources, such as district heating, the decentralized character is lost or at least weakened.

At the other extreme, natural gas systems are similar to electric power grids, with remote production centers feeding into national pipeline systems which then supply regional utilities selling to individual consumers. Oil distribution systems, however, are not so clearly definable. Although production, refining and national distribution are remote and centralized, local distribution is generally by individual and competitive companies, a factor that adds a degree of control and decentralized influence to the individual consumer.

Ownership

Degree of decentralization could also be measured in terms of who owns the equipment. Ownership by the end user could be defined as the most decentralized; other forms of ownership could be by the nonuser, or joint ownership between the user and nonuser. Further differentiation can be made in terms of the character of the nonusing owner: whether he is the exclusive supplier or whether there are several competitive sources of supply.

Use of this definition helps to deal with the question of independence mentioned above. End-user ownership would give the greatest degree of independence, especially for technologies that do not require fuels, such as solar heating or on-site biogas production. Industrial cogeneration facilities would also give some degree of independence to the user, but would be dependent on suppliers of fuel. In addition, as with other technologies, cogeneration as generally practiced may be tied into a central grid or otherwise operate in conjunction with other energy sources, thus reducing the independent, or decentralized, character of the system

Main energy form

Decentralized technology is sometimes used implicitly as synonymous with renewable energy sources. In some cases, such as solar energy, this definition is adequate, although once again the question of back-up or combination with other energy sources could weaken the degree of decentralization. For other renewable sources, however, such as biogas or methanol from wastes, a centralized production and distribution system similar to the present oil and gasoline system could become the dominant mode of use.

Effect on central electric power

A broader definition of a decentralized technology is one that, in one way or another, reduces the amount of centrally generated electricity, or reduces the concentration of electric generation systems, either in terms of location or ownership. This is the definition that was used to compile the catalog of technologies described earlier.

In general, decentralized technologies by this definition can be arranged in five major groups, according to the extent to which they replace electricity use and whether they operate independently of central electric power or in conjunction with it. Table 1 illustrates this organization and indicates some of the technologies that fit in the various categories.

Some technologies have the potential of meeting all the energy needs of a particular function at a dispersed installation; others may replace some of the energy that might otherwise be supplied by electricity or other energy sources, but would require backup energy, either electricity or another source. In each case some technologies would operate independently of the central electric grid, while others would operate in conjunction with the electric power utility system A third category would consist of technologies operating within the electric power sector that could lead to a more dispersed system without reducing central electricity use.

VALUE MEASURES AND GOALS OF DECENTRALIZATION

A number of reasons have been advanced for pursuing decentralized technologies or decentralization of electric power generation. To put these goals in perspective, it is necessary first to consider the value measures used in determining general energy policy and in making energy supply and consumption decisions. In discussing these factors it is convenient to divide value measures into three basic categories: individual values, national goals, and long-term social goals. A generally complementary organization would be to divide them into short-term, medium-term and long-term goals.

Individual values

At the individual or end-user level, the immediate measures of the value of energy sources lie in judgments of cost, convenience, reliability and independence. Choices among energy sources entail a balancing of these factors, and the outcome will vary depending on the weight assigned to each. Thus some energy users may be willing to sacrifice some convenience for the sake of a lower price, or give up a degree of reliability for independence, while others may come to the opposite decision. To a certain extent, these values are interdependent: greater convenience, for instance, even if more costly, could lead to cost savings elsewhere and so be worth the extra expense.

TABLE 1.—TYPOLOGY OF DECENTRALIZATION TECHNOLOGIES (WITH EXAMPLES)

Function	Replace central electricity completely		Reduce use or growth but not eliminate		Not reduce use or growth but reduce central plant growth
	Independent	Combined	Independent	Combined	
Household/commercial space heating and cooling	Cogeneration	Dist. heat	Insulation; Passive and active solar		
Household/commercial electricity	Cogeneration; fuel cells; photovoltaic				
Industry: Process heat	Coal gas and liquids; wood and waste	Cogeneration	Solar	Waste heat	
Industry: Mechanical				Small hydro	
Industry: Electricity	Small hydro	Cogeneration			
Transportation	Biomass; synthetics				
Electricity generation					Medium-size coal; fuel cells; wind.

Such decisions are usually made on the basis of rather short-term views of the future. This factor is important in judging technologies because some involve a high initial investment with deferred savings in operation and fuel costs, while others cost less to install but more to operate. The tendency of most individuals, and some corporations, is to keep today's capital investment low and take a chance on tomorrow's operating costs.* This is another way of saying that the discount rate—the value of a dollar today compared to a greater sum a few years hence—is rather high, particularly when investment capital is extremely expensive, as it is at present. This factor extends even to investments for which pay-back is rapid, as it may be in the case of home insulation. Frequently some kind of incentive is effective or necessary to overcome individual reluctance to invest in fuel-saving technologies.

Of the four value measures listed, only independence is directly served by decentralization. Cost, convenience or reliability are not necessarily related to degree of decentralization: specific decentralized technologies may be more or less costly, convenient or reliable than centralized energy supplies, but these characteristics do not derive from decentralization as such. In addition, in most cases independence is probably the weakest factor in deciding which energy source to choose, if the other three are satisfactory, and if they appear likely to remain so in the future. However, if cost or reliability of supply appears likely to deteriorate in the near future—for instance, if oil or gas availbility is problematical or if prices of central electricity seem likely to increase sharply—then an independent energy source might take on enough added value to be chosen even if the other factors were negative. Once again, such judgments are usually based on short-term views of future developments.

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*At the corporate level, for utilities particularly, there is a countervailing pressure to invest in capital-intensive facilities, since the rate structure rewards this type of operation. In their present precarious financial state, however, and with the cost of capital so high, this factor is considerably weakened.

National goals

Energy policy goals, as expressed in the National Energy Plan, include reducing dependence on imported oil, protecting the environment, and stimulating economic growth. These are national rather than individual goals because, although individuals may agree that they should be pursued, they can be achieved only through aggregated action of a large number of individuals.

Because these goals are national in character, they have less influence on individual decisions than factors that bear directly on the individual. For this reason, many energy policy proposals attempt to achieve their goals by influencing individual decisions through short-term factors such as price or availability. One of the major difficulties in developing acceptable energy policies is that initiatives designed for one purpose—increasing oil prices to reduce consumption, for instance—may have a negative effect on another—such as controlling inflation and stimulating economic growth.[7]

The energy goals expressed in the National Energy Plan do not necessarily favor either centralized or decentralized technologies as such—unless decentralization is considered synomymous with renewable energy sources, a definition that was shown earlier to be not very satisfactory. A given technology may either further or hinder efforts to reduce oil imports, may have either greater or less environmental impact, or have more or less effect on economic growth, exclusive of whether it is decentralized.

Long-term social goals

The focus of the National Energy Plan, and of most energy planning, is on the mid-term future; most of the targets of the NEP, for instance, are for 1985. There are a number of longer-term goals, however, which may be influencial in determining mid-term policy decisions, but which tend to be obscured in the common preoccupation with the immediate or middle-term future. These long-term social goals tend to be highly controversial.

Decentralization itself is one such proposed social goal: decentralization for the institutional purposes of reducing the concentration of social and economic power and bringing decision-making in the field of energy closer to the influence of the consumer. But there are other social purposes which, it could be argued, could be furthered by decentralization, in the broad sense of reducing the amount and concentration of central electric power generation

One of the most pervasive long-term social issues is the question of the limits to growth, not only of energy consumption but of population, resource consumption, and even of the economy. The limits-to-growth concept was forcefully articulated in the early 1970's as part of the environmental movement; the result was an active debate in which the imminence of such limits was strongly challenged. That debate was never resolved, although it is no longer as active as it once was. The concept, however, lies behind many of the attitudes that find expression in arguments over today's more immediate problems, such as energy policy.

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[7] Gushee, David E. Will the Real Energy Problem Please Stand Up? Chemtech, August 1978, pp. 474–477.

One of the most significant examples of the implicit residual influence of the limits-to-growth debate is found in Amory Lovins' soft path model. Lovins asserts that limits-to-growth concepts "are not part of my thesis . . . , are neither necessary nor important to its argument, and were not uppermost in my mind when I wrote it." He adds, however, that "these concepts are an important part of the intellectual life of my time, and any thinker is inevitably a product of his or her time. . . ." [8]

Industry analysts, on the other hand, tend to reject the limits-to-growth argument as a basis for policy decisions. A study by the Edison Electric Institute, for instance, found that continued economic growth was sustainable, desirable, and necessary, and concluded that "the potential limiting factors of natural resource scarcities, population growth, food production, land availability, pollution, psychological and organizational limits, and the entropy law, can be managed in ways which will allow desirable forms of moderate economic growth to be sustained for the foreseeable future." [9]

Halting the use of nuclear power is another widely held social goal. For many who accept that goal, opposition to nuclear energy is so broadly conceived and unyielding as to be beyond debate. Although part of this opposition is based on concerns about safety and the environmental hazards posed by radioactive wastes, the major negative aspect of nuclear power for many critics is based on its connection with nuclear weapons and the threat of nuclear war. Lovins, for example, devotes some of his most eloquent language to the topic:

"We now cower under the threat that, through a moment of error, terror or madness, thousands of small stars will be kindled here and there on the surface of our planet. A few incandescent hours—followed by withering, lingering clouds of poison—could rend the cultural fabric of thousands of years and much of the biological fabric of billions." [10]

Lovins proceeds from this premise to argue that by cutting off the peaceful atom, proliferation of nuclear weapons can be stopped. There are only two choices, he says: world government with world control of nuclear weapons and nuclear power, or complete abandonment of both.[11] The latter he finds much more desirable, and he argues that complete "denuclearization" is attainable if the soft path is followed.

He rejects as unworkable and ineffective the efforts that have been taken so far, including the Non-Proliferation Treaty, to restrict the spread of nuclear weapons, calling them "deeply flawed." [12] Only a society based on the soft path will have the characteristics that will enable the world to eliminate nuclear weapons, and nuclear energy, entirely:

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[8] Lovins, Amory B. Comments on two reports by Carl E. Behrens. In U.S. Congress. Senate. Select Committee on Small Business and Committee on Interior and Insular Affairs. Alternative Long-Range Energy Strategies. Joint Hearing, December 9, 1976. Washington: U.S. Gov. Print. Off. 1977. p. 707.

[9] Edison Electric Institute. Economic Growth in the Future: The Growth Debate in National and Global Perspective. New York: McGraw-Hill, 1976.

[10] Lovins, Soft Energy Paths, op. cit., p. 171.

[11] Ibid., p. 198.

[12] Ibid., pp. 193–194.

"The methodical collapse of nuclear power under its own weight [13] now offers us, briefly, the chance to start afresh; the chance to go back and deal more wisely with the consequences of the first Promethean visit before we are incinerated by the second. But the political opportunity we now enjoy will soon pass by and will never come again. . . . Putting the nuclear genie back in the bottle . . . is a prerequisite for everything else, the most urgent issue of this or any age." [14]

Lovins' style is unique, but the views he holds are widely, if less dramatically, expressed. For those who believe with him that the only alternative to halting all use of nuclear energy is radioactive incineration, the nuclear issue becomes nonnegotiable. Those who consider his fears overdrawn and his "denuclearization" goal utopian, on the other hand, tend to reject his proposals completely and dismiss his voluminous statistics as biased and unreliable.

Another long-term social goal is resource conservation. The conservation ethic is a well-established part of American culture, but it has been at constant war with the basic character if America as the land of plenty and, more recently, the land of convenience—an image that has caused American civilization to be described as a "throwaway" society. Environmental concerns and the perceived shortages of many resources lend support to the conservation goal, as does the concept of limits to growth in general. These are middle- and long-term values, however, while convenience is measured in the short term.

Resource conservation as a general principle is different in quality from conservation of particular resources, such as oil or uranium. Cutting back on the consumption of oil for a particular purpose—such as reducing the need for imports—is a middle-term national goal that can be affected by changing conditions and new perceptions of future needs and supplies; the long-term social goal represented by the conservation ethic is less flexible, and uninfluenced by the argument that a particular resource appears to be in plentiful supply. It also tends to be an implicit factor in debate, rather than being explicitly stated.

Goals and policy

The preceeding discussion has divided the goals and values that determine energy decision-making into short-term, middle-term, and long-term categories, and drawn a parallel comparison on the basis of individual, national, and social goals. Individual decisions are made largely on the basis of their short-term effects, and factors such as cost, convenience, reliability and independence are the most powerful in influencing those decisions. National policy decisions are concerned with the mid-term future, and are often designed to affect short-term factors so as to influence individual decision-making in the direction desired. Long-term social goals are rarely the subject of legislative policy making, but they frequently influence policy-makers in ways that are not always explicit.

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[13] Lovins' more recent work has been devoted to demonstrating that soft path technology is not only desirable but economically competitive. Lovins, Amory B. Soft Energy Technologies. In Hollander, Jack M., et. al. (eds.). Annual Review of Energy. Volume 3. 1978. Palo Alto: Annual Reviews Inc., 1978.

[14] Lovins, Soft Energy Paths, op. cit., p. 217.

These three types of goals differ in another dimension: the degree of controversy involved in determining their validity. Debate can take place over the short-term, immediate cost or reliability of a technology, but such disagreements often can be resolved by reference to available data. Debate over medium-term national energy goals can be vigorous, partly because of the less precise information available to aid in making decisions. But even national policy is much more amenable to resolution than long-term social controversies such as the limits to growth, nuclear power and nuclear proliferation, and general conservation principles.

Decentralizing electric energy production would have little effect on any of the cited short-term or middle-term goa's other than individual independence; that is, any such effects a particular technology had on those goals would derive not from its decentralized character but from other qualities. The potential effect on growth and on conservation is less clear, primarily because those goals are more difficult to define and measure. But decentralization as a goal in itself is a long-term social value, and it would have a direct effect on another long-term goal cited earlier: the shutting down of nuclear power generation.

The fact that decentralization has most of its effect on long-term social goals complicates the debate over whether and to what degree it should be pursued, since those goals are themselves so controversial. Another aspect is the effect of such efforts on the future of the electric utility industry. The next sections deal with this aspect of the decentralization question.

CENTRALIZATION TRENDS AND DECENTRALIZING FACTORS*

The electric utility industry started as a highly decentralized activity with generation located close to the consumer, and with virtually no interties between systems. As technology advanced, however, economies of scale became of considerable importance. The industry then moved toward mergers and interconnection. This allowed construction of relatively large sized generating units, as well as higher voltage transmission lines. As a consequence, by 1932, eight holding companies produced 75% of our electric output. Shortly thereafter several became bankrupt due to the drop in sales resulting from the decline in economic activity during the Depression period. This traumatic period was followed by one of vigorous growth and expansion, spurred by steadily declining costs. For example, average revenue per kWh sold declined from 2.88 cents in 1950 to 2.10 cents in 1970 for residential customers.[15] Sales to those customers rose from 70 billion kWh to 448 billion kWh in the same period. The trend for commercial and industrial customers was similar.

The lower costs were generally achieved by moving to larger, more efficient units. The number of privately owned steam plants over 500 MW increased from 155 in 1950 to 222 in 1975, while those in the 100-MW to 500-MW range dropped from 287 to 255, and those under 100 MW declined from 219 to 154. During this period, average energy consumption by generating units dropped from more than 15,00 Btu per kWh to 10,600.[16]

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*This section was prepared by Alvin Kaufman and Susan J. Bodilly.

[15] U.S. Bureau of the Census. Statistical Abstract of the United States, 1977. Washington, D.C., 1977, p. 601 and 603.

[16] U.S. Department of the Interior. Energy Perspectives 2. June 1976, p. 73 and 129.

At the same time, transmission voltages moved upward. In 1950, there were 8.2 thousand miles of transmission lines rated at 230 Kv or above; by 1970 there were 65,400 miles, of which one-third were over 345 Kv. The reason for this growth is not hard to find: Electricity can be transmitted over a 765-Kv line for 300 miles as effectively as over a 138-Kv line for 10 miles. It has been estimated that 4,000 MW should be moved 200 miles over a 765-Kv line for less than 1 mill per kWh; to move 1,000 MW over the same distance using a 500-kV line would cost about 1.25 mills per kWh. Conversely, movement of 1,000 MW over the 765-Kv line would cost close to 1.5 mills per kWh.[17]

The result of these perceived economies has been a decrease in the number of investor-owned utilities from 405 in 1968 to 366 in 1975 due to mergers. This decline is part of a trend that began as early as 1927, when there were 2135 companies. Most of the private companies are independently owned and operated, although 80 are subsidiaries of holding companies or other corporations.

In addition to the merger trend, utilities have undertaken interconnections. In some cases interconnection is for operation and investment-economy through integration of the systems. The bulk of the interconnections are for reliability and for providing a source of emergency power, and resulted in three networks, one each in the East and the West, and a third in Texas.

The centrally dispatched systems tend to be located in the East and comprise about one-third of U.S. generating capacity. There is a movement to compel addition interties and central dispatch. This move has been spurred by the high cost of new facilities and the resulting need to share the risk. In any case, the trend toward interconnection of systems, at least for reliability, seems well established.

Offsetting the above trends has been a steady escalation in costs over the past few years. Whether this signals the exahustion of economies of scale is not yet known. Some contend the rapid escalation of construction costs, rise in interest rates, and strict pollution requirements makes small beautiful. Others feel a substantial portion of the cost rise is the result of the introduction of new technologies such as nuclear energy, higher temperature and pressure conventional units, higher voltage transmission, etc. These people would expect electric costs to decline in real terms once the introductory phase is over. It is still too early to decide who is right.

Despite this question, it is clear that utility demand will grow at slower rates than in the past. This will occur not only because of the substantially higher prices for electricity, but due to slower population growth and to the conservation ethic.

Slower population growth will decrease demand growth, making it less necessary to build new plant and reducing the incentive to invest and innovate. Offsetting this trend, however, is an increase in the number of people living alone and in the number of women in the workplace. One could theorize that low-cost energy spurred the development and use of appliances. Thus freed from onerous housework and perhaps under pressure to help balance the family budget, women moved out to work, thus creating a demand for more appliances and more electricity. As this social revolution continues to press the need for more single-person living space, appliances, etc., the need for electricity may increase.

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[17] Much of the material in this section is derived from U.S. Library of Congress. Congressional Research Service. National Energy Transportation. Vol. 1. Current Systems and Movements. Committee Print of the Senate Committee on Energy and Natural Resources and Committee on Commerce, Science and Transportation. Washington: U.S. Govt. Print. Off. May 1977, pp. 347–376.

Other factors influencing the use of electricity, and the role of centralized electric power, have been created by law. Among these is the 10% tax credit on new investment granted on Federal income taxes, and other tax incentives. These tend to make it more advantageous to build large centralized units and necessary transmission by subsidizing the cost through the tax system. That is, less capital needs to be borrowed since retained earnings will be higher, and the company's tax bill lower. This advantage is offset somewhat by the recently enacted credit for solar units.

In addition, in recent years government regulation has added extra costs to the production of electricity in the form of environmental protection costs, worker safety costs, etc. It has been argued that these costs of regulation have had the impact of raising fuel and generation costs to the utilities. For instance, it is charged that increasing environmental, siting and safety regulation has brought nuclear plant construction to a standstill in many areas. Increased strictness of environmental controls on coal mining and coal-fired plants have made them more and more costly to build and operate. These government regulations have in effect discouraged large scale power technologies by increasing costs or by stopping construction completely. Some dispersed technologies face fewer difficilties in these regulatory areas, although they may have other regulatory problems.

Rate design is another factor affecting the question of centralization of electric power generation. The electric utilities are currently in the throes of a rate reform movement. This has been further encouraged by the requirements of the National Energy Act. Many state commissions have held hearings on the advisability of revising the traditional rate design to a system based on time-of-use. A major issue in these cases has also been the kind of cost to be used as a basis for ratemaking. There is strong advocacy for the use of marginal cost in place of the current average cost. Marginal cost is the cost of producing the last unit. In many of the rate cases it appears to be defined as the cost of the next increment of capacity due on line, or as the cost of the last unit needed to meet the peak demand.

Generally, the adoption of a marginal cost system would require a time-of-use (TOU) rate design, although such a design could also be based on average cost. A TOU design would require a higher price for energy based on peak (when costs are higher) than off-peak. The peak period for most utilities currently occurs during the afternoon. TOU pricing, by charging the customer more for this period of use, could make decentralization more attractive. By installing an alternative decentralized system, such as solar power, the customer could avoid the high peaking costs, coming back onto the central system when off-peak rates were in effect to recharge storage and operate a back-up system. This would depend on the way rates were structured and the differential between the peak and off-peak rates.

PRESENT STATE OF THE ELECTRIC UTILITY INDUSTRY*

Fuel consumption patterns

Throughout the growth of electric power generation, the sources of power have included coal, oil, natural gas and hydroelectric energy, and these four sources, with the addition of nuclear power, still contribute the overwhelming share of energy at present. Table 2 indicates the proportion of electricity generated by each of these sources during 1977 and the first eight months of 1978.

TABLE 2.—ELECTRICITY PRODUCTION IN THE UNITED STATES, 1977 AND 1978, BY ENERGY SOURCE

Source	1977		1978	
	Billion kilowatt-hours	Percent	Billion kilowatt-hours	Percent
Hydroelectric	220.5	10.4	280.8	12.7
Coal	985.5	46.4	975.7	44.2
Petroleum	357.9	16.8	365.0	16.6
Gas	305.5	14.2	305.0	13.8
Nuclear	250.9	11.8	276.4	12.5
Other [1]	4.1	.2	3.3	.1
Total	2,124.4	100.0	2,206.2	100.0

[1] Includes generation by geothermal, wood and waste.

Source: U.S. Department of Energy. Monthly Energy Review. DOE/EIA-0035/4(79). April 1979.

The data indicate that coal is the primary fuel for electric power generation, but that oil and gas contribute close to one-third of the energy required. The 1978 data are a more accurate reflection of hydroelectric generation than 1977, a year in which severe Western drought caused low production from this source. On the other hand, the coal strike affected the share of electricity produced by that source in 1978.

Although the national figures represented in Table 2 are significant, they conceal the broad variation of fuel sources among different regions of the country. Table 3 presents the production of electricity by source on a regional basis for the month of August 1978.

TABLE 3.—PROPORTION OF ELECTRIC PRODUCTION BY SOURCE, AND TOTAL PRODUCTION, AUGUST 1978, BY REGION

Region	Hydro-electric (percent)	Coal (percent)	Oil (percent)	Gas (percent)	Nuclear (percent)	Total (billion kilowatt-hours)
New England	2.9	1.2	61.9	0.3	33.5	6.5
Middle Atlantic	8.2	40.1	32.1		24.8	24.7
East North Central		76.8	4.2	1.1	16.9	35.8
West North Central	9.9	65.0	1.8	11.1	12.0	15.0
South Atlantic	3.4	50.5	24.2	3.9	17.7	37.6
East South Central	9.0	70.1	6.5	2.4	11.8	19.5
West South Central	1.1	14.6	7.6	74.6	1.9	29.8
Mountain	22.7	61.4	3.0	12.6		13.3
Pacific [1]	51.7	2.0	20.6	19.0	5.2	22.5
Hawaii and Alaska	5.5	3.2	76.7	14.3		.8
United States	10.8	45.4	15.7	15.8	12.5	205.6

[1] 1.3 percent produced by geothermal and wood and waste.

Source: U.S. Department of Energy. Energy Data Report DOE/EIA-0005/8 (78). Published November 1978.

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*Prepared by Carl E. Behrens.

These data demonstrate the regional differences in sources of energy for electric production. Coal is the dominant fuel in six regions, but is hardly used at all in three others. It is used only moderately in the West South Central region, where natural gas supplies three-fourths of the energy for electric power. (Only a few years ago, more than 90% of electricity in the West South Central region was produced from gas.) Oil is an important source in the Atlantic and Pacific regions, but used relatively little in the Central and Mountain States. Nuclear power is most significant in the Eastern half of the country. In the Pacific region, half the electricity produced comes from hydro power.

Economic constraints

Instability has been a major characteristic of the electric utility industry since the 1973 oil embargo. Prior to that time, the electricity industry had been growing at a rate faster than the growth in the gross national product and in energy consumption, and utilities were looked on as steady, reliable ventures that would rarely face serious disturbances. The cost of producing electricity was declining in real terms, as was the price of oil and natural gas. New additions to generating capacity were generally more efficient than existing facilities. As a result, if overoptimistic projections of future growth caused excess capacity, the surplus capacity could usually be sold to other utilities at attractive prices, or savings could be achieved by retiring older, inefficient facilities. The utilities were subject to regulation, but in an era of decreasing costs and rapidly growing markets, regulation was no burden. Furthermore, the regulation was not concerned with siting of plants, but with rate-setting.

The contrast between that earlier period of stability and growth and the present situation of the electric utility industry could hardly be greater.

The developments that have contributed to the current difficulties began with the environmental movement of the 1960's and the consequent involvement of the Federal Government in questions of power plant siting, design, and environmental effects. This Federal involvement in siting began with the Federal regulation of commercial nuclear power, and later involved other Federal agencies, particularly the Environmental Protection Agency, which was concerned with all types of generating facilities. Accompanying this Federal involvement was an increasing interest on the part of the State authorities in environmental and siting questions.

The environmental regulations affected the climate in which utilities had to operate. The Arab oil embargo and the astronomical rise in oil prices that accompanied it revolutionized the industry, even those parts of it that were not heavily dependent on oil. Coal prices followed the rise of oil costs, and the general inflation and recession that ensued affected the industry as a whole.

Electricity consumption grew hardly at all during 1974 and 1975. As a result, utility cash flow was reduced below expectations and caused most utility stocks to fall sharply, making it difficult for them to obtain capital on the equity market. Uncertainty regarding future markets added to the cost of capital. At the same time, construction costs were going up, and a capital shortage made it extremely expensive for utilities to obtain money by issuing bonds. Electricity prices increased rapidly because of fuel adjustment clauses, which allowed utilities to pass through the higher fuel costs directly to the consumer without requiring regulatory approval of changes in the rates. The result was a reluctance on the part of utility regulators to grant rapid rate increases to compensate for increases in other costs—particularly since the rate increases would go to fund capacity that would not come on line for a substantial number of years.

All these factors produced a financial squeeze on most utilities that could only be relieved by deferring or cancelling planned construction of future generating capacity. Even if the growth rate of electricity consumption had not dropped, the financial status of utilities with large construction plans would probably have required these deferrals.

The economic situation improved somewhat in 1976, as economic recovery was accompanied by a growth in electric power consumption of 6.2 percent. Inflation and interest rates were less than they were during the "stagflation" years, and rate increases led to some recovery in utility stocks. But 1977 consumption increased by only 4.9 percent and by 1978 inflation and interest rates were once again high, the stocks of utilities were down, and consumption for the first eight months of the year was only 3.2 percent above the consumption of the same months in 1977.

Thus the financial problems of the industry remain, and their situation is not encouraging .The main feature of these problems is a much higher level of uncertainty in estimates for future demand and the ability to supply it, which complicates the planning process and makes it more difficult to obtain capital for future construction.

Four kinds of uncertainty

One form is uncertainty in future demand. The variability of demand since the oil embargo, and the indecisiveness of national energy policy regarding electricity's role in the future, have made it difficult to project demand for more than about five years, a time formerly reasonable for construction planning. At the same time, because of longer construction times for nuclear and coal power plants, the projections must extend 10 years or more. Unfortunately, the facilities that can be constructed rapidly and with lower capital investment are those fueled with oil or natural gas, which utilities are reluctant to commit themselves to for reasons of price or doubtful availability.

Furthermore, the consequences of overestimating, or underestimating, future load growth have increased. Since nuclear plants are large and expensive, they come on line in large units, reducing the utility's flexibility to adjust to short-term variations in load growth. If the new unit pushes the utility's reserve capacity too high, it is burdened with a large capital investment on which it is gaining no return—an effect that is augmented by the fact that in nuclear power the economies of the technology lie in the low cost of fuel, and are only realized if the plant is operated.

Scheduling is another uncertainty. Estimates of construction times are extremely unreliable, particularly with nuclear units and increasingly with coal-fired plants. There is at present no way of determining how long it takes to build a nuclear unit, because the deferrals in construction schedules of the last several years have been caused mostly by financial difficulties or reductions in estimates of future load growth.[18] There is no doubt, however, that in many cases opposition and regulatory difficulties have added to construction times. Planning for future plants in light of experience so far involves serious imponderables which may or may not be reduced in the future.

Another uncertainly lies in estimates of the cost of new units and of alternatives to new units. A major factor is the possibility of delays in construction, for the various reasons cited above, which in the presence of rapid inflation and high cost of capital can have a very large effect on the ultimate cost of the unit. This factor is particularly important when a utility is trying to decide between a nuclear unit, which appears to have a cost advantage, and another type of facility which may be easier to site and construct. Uncertainty about the future price of alternative fuels, such as oil or coal, also contributes to the difficulty in estimating relative costs.

A fourth area of uncertainty lies in the role of electricity in the evolving national energy picture. Events since the oil embargo indicate that the historical growth of the 1950's and 1960's will not resume. But it is not clear what that growth rate will be, nor how it will be influenced by national policy.

The attitude of many policy makers toward electricity is equivocal. On the one hand, electricity produced from nonpetroleum fuels would appear to have a strong role to play in achieving a major goal of the Administration's energy policy, which is to reduce U.S. dependence on imported oil. However, there are numerous forces in opposition to rapid substitution of electricity for petroleum fuels. Higher costs of electricity are a major factor. Combined with active consumer resistance to increasing rates, financial factors have already caused substantial slowing down of construction of new capacity, and this trend can be expected to continue.

There is additional challenge to the concept of centralized power stations and large electric power grids—the topic of this study. Electricity produced by fossil fuels is also questioned because of the large energy losses involved in the conversion, compared to the direct use of these fuels to produce heat. This questioning of central power is sometimes extended to all sources of electricity, including uranium or hydropower, on the grounds that if overall consumption were less the difference could be taken out of the fossil generation.

ECONOMICS OF DECENTRALIZED TECHNOLOGIES

If a choice were to be made between decentralized and centralized technologies on strictly economic terms, leaving out consideration of social and environmental aspects, then the predominant factor would appear to be the relative cost of supplying the necessary energy—although economic decisions are always affected by factors in addition to price. In view of the difficulties and uncertainties facing utilities today, however, it is possible that even in economic terms a decentralized system could overcome a price disadvantage by easing some of the uncertainties discussed in the previous section.

Of the four uncertainties mentioned, the first, uncertain demand, is the area in which most decentralized technologies would have the clearest advantage. To the extent that they are added in smaller units, these technologies would offer more flexibility in dealing with changes in projected demand for energy. Meeting demand as it developed would be easier, and the penalty for overbuilding would be less.

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[18] Behrens, Carl E. The Role of Licensing in Nuclear Plant Construction Times. Congressional Research Service, Oct. 20, 1977.

Uncertainties in scheduling, and in estimating costs—the second and third items mentioned above—are less likely to be improved in going to decentralized technologies. Although once again smaller units tend to be built more rapidly and with less scope for cost overruns, these advantages may be offset if the decentralized system is a new technology that is in the process of development and improvement. In such cases delays and cost increases may be considerable and unpredictable. Nor is the capital-intensive character of many of these technologies, particularly those based on renewable resources, an advantage in either estimating costs or scheduling; in fact, in this regard they share the difficulties that accompany the construction of nuclear plants, which depend on saving of operating costs for their economic advantage.

In the fourth area, national energy policy, decentralized facilities would seem to have a strong advantage. Yet even here, the new technologies, dependent as they are at present for development on Government programs, are vulnerable to changes in policy which could seriously alter perceived economic advantages.

EFFECT OF DECENTRALIZATION ON UTILITIES*

The impact of decentralization, should it occur, depends on the time period under consideration. That is, over the long term it can be assumed that the utilities would have adjusted to the new conditions, and impacts would be minimal. In the short and intermediate term, however, the effect of decentralization would be traumatic. We define this period as the time required to bring a new plant on-line, roughly 8 to 14 years.

We assume that however decentralization takes shape, a centralized system of some kind will still be required to provide back-up energy and to serve those customers who do not find decentralization feasible. The particular impact on an electrical system is dependent on the specific characteristics of the system. Generally, however, if the decentralized installation were able to provide for all of the electrical needs of its locale, the impact on the utility would be a loss of revenue, and the prospect of shrinking sales.

On the other hand, if the decentralized installation could meet all the requirements except at the peak, and this peak coincided with the utility peak, the utility would suffer a drop in load factor. This would mean more of the utility's capacity was sitting idle in the off-peak period, resulting in higher costs due to the reduced efficiency.

A more likely scenario, however, is the need for back-up energy by the decentralized user off peak. In this situation, the utility would benefit in terms of improved load factor. This assumes that the decentralized energy users do not create a peak, thus requiring more centralized generation.

As decentralization proceeded, the utilities would find themselves with overcapacity for a time, which as they currently are overbuilt due to the impact of conservation. Rates would have to rise to keep revenues up in order to make bond payments and meet interest coverage requirements. The increased rates will cause demand to decline even more, creating the proverbial vicious circle.

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*This section was prepared by Alvin Kaufman and Susan J. Bodilly.

A major impact on the utilities will be the result of the uncertainty engendered by decentralization. This would make it difficult for a company and its regulatory body to decide what, where and when to build. It would also make it extremely difficult for the company to finance construction. Investors and lenders will be wary of putting money into an industry whose future is uncertain, and whose present profits are equally uncertain. Those who did would demand a premium commensurate with the risk.

In this regard it should be noted that the utilities are among the most capital intensive industries in the country. The electric companies are responsible for 17% of the total annual U.S. expenditures on new plant and equipment. In 1976, they invested $17 billion or 12% of their net plant; 70% of these funds were obtained from the capital markets. It has been estimated that if capacity grew at 5% per year, new book capital would have to grow at 10%.[19] This implies capital expenditures of more than $35 billion in 1986.

All in all, decentralization presents the utilities with a mixed bag. On the one hand, their capital requirements would be reduced and their profits increased. On the other hand, they would have difficulty raising money for expansion and will have problems forecasting, and meeting, demand—problems that already plague the industry to a serious degree.

SUMMARY: ELECTRICITY AND DECENTRALIZATION*

This study has been an attempt to place the issue of decentralization in the context of energy decision-making, on the individual level, and energy policy-making, on the national and social level. It has been seen that decentralization has most of its effect on long-term social goals, which are the subject of a great deal of controversy.

It has also been seen that the future role of electric power in the national energy system is highly uncertain, and that those uncertainties will be resolved in part as a result of decisions on the desirability of decentralization, and on the long-term social goals that are affected by it.

Another aspect of the decentralization issue is its effect on the electric utility industry. Even those who view decentralization as a means of sharply reducing the role of electricity in the energy system probably accept the usefulness of a vestigal central electric grid to serve areas where independent electric supplies are impractical. The many financial and technical difficulties facing the utility industry at present raise the question of the ability of that industry to supply reliable electric power in the future, particularly in the face of growing competition from other energy sources, centralized or decentralized, and energy policy decisions based on a general approach that electricity is a wasteful form of energy. A parallel may be drawn between the electric utility system today and the railroad system, another regulated industry, following World War II. The present state of U.S. railroads is traceable to that industry's inability to cope with competition from other technologies, exacerbated by regulation and controls that had been imposed when the railroads were powerful, indispensable and economically prosperous.

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[19] Stelzer, Irwin M. The Electric Utilities Face the Next 20 Years. National Economic Research Assoc., Inc. September 1978, p. 4–5.

* Prepared by Carl E. Behrens.

A comparable situation may be said to have faced electric utilities since 1973, except that their problems have been created not so much by competition from other energy sources but by the radical change in utility economics brought on by astronomically high oil prices and other components of the post-embargo energy crisis.

Thus decentralization, in the broad sense of reducing the amount of centrally generated electricity, would have to be applied with considerable caution to avoid a decline in reliability and service in the utility industry comparable to that which has occurred in the railroad system.

In a more restricted sense, individual technologies may be desirable on the basis of factors other than their decentralized character—factors such as price or environmental qualities or their role in achieving national energy policy goals. In addition, it has been seen that, within the utility system itself, decentralizing facilities for producing electricity for a central grid may have some advantages, such as making the system more flexible for changing projections of load growth and reducing the capital investment involved in a single commitment to a new facility.

DIVERGING OR PARALLEL ROADS?

The articles that follow have been selected to illustrate and expand on the themes discussed in this introductory essay. The selections are divided into several topics, and each selection is preceded by a short summary of the content of the article and commentary on its relevance and significance.

The first group of articles concerns general energy policy, and include two selections by Amory Lovins. The second topic is the electric utility industry, and the articles in this group discuss various aspects of utility operations and future. Three groups of articles on decentralized technologies follow: solar energy, congeneration and waste heat utilization, and conservation. A final article on "soft path" technologies rounds out the collection.

Besides holding interest of their own, these articles demonstrate vividly the deep divergence of opinion over the role of central electric power generation in the future U.S. energy picture. Any discussion of decentralization, to be meaningful, must deal with this divergence of opinion.

The purpose of this volume is to stimulate consideration of the question: Can decentralized energy systems be developed in parallel with the present centralized system, or are the two basically incompatible? If both do appear to have a role in the energy system, then a further task is to discover means of overcoming the mutual obstacles which each seems to pose to the other.

GENERAL ENERGY POLICY—I

(By Kenneth E. Boulding)

Some philosophers are analysts; others are synthesists. The analyst pulls a problem apart and shows us its pieces and their individual attributes. The synthesist takes the pieces of fact at hand and builds a construct, a theory, or, more modestly, a paradigm or model. Some, of course, are both analysts and synthesists.

Kenneth Boulding, in this article, is an analyst. He separates the process of decision-making, describes the characteristics of decision makers, discusses the influences—sociological, psychological, historical—that affect their actions, and relates his discussion to energy and the making of energy policy.

Analysis, unlike the work of synthesists such as Amory Lovins (represented later in this collection), makes for difficult reading. The reader comes away from analysis not with the comforting feeling of having learned of an apparently logical and plausible representation of reality, but with the suspicion that no matter what he later decides is the truth, he will be wrong—or at best only partially right.

Those who feel that such a frustrating exercise is not worth the effort may want to move on immediately to the sections that deal directly with the subject at hand. There are compensations for perseverence, however: the pleasure of Boulding's description of human history as "a never-ending process of evolutionary disequilibrium"; the stimulation of his assertion that "decisions of powerful people are almost doomed to be bad"; or the consolation that "all persuasion, one hopes, will ultimately fall victim to truth, though it does seem to take an unconscionably long time."

[Excerpt from "Future Strategies for Energy Development," Oak Ridge, Tenn., Oct. 20 and 21, 1976]

DETERMINANTS OF ENERGY STRATEGIES

(By Kenneth E. Boulding)

Strategy is a decision about decisions. Shaving is a decision; being clean shaven is a strategy. Getting up in the morning is a decision; taking a job is a strategy that affects our decision about getting up in the morning. Building a nuclear plant might be the result of a decision; a nuclear moratorium would be a strategy.

Energy strategy, like all others, almost certainly for good rather than for ill, is not the decision of any single person. It emerges as a result of the interaction of a very large number of the 4 billion decision-makers of the human race, some of whom of course are more powerful, that is, affect more people more strongly, than are others. The dynamic processes by which the role of energy in society is changed may be affected in a small way even by this conference. They may be affected more by the decisions of the powerful, like the people who make the decisions for the Organization of Petroleum Exporting Countries. They are also affected by the political and social climate, and by the fashions of opinion or behavior that affect the decisions of the powerless, who collectively make far more difference to the world than do the decisions of the powerful. Power, one suspects, is 99 percent illusion, though of course the 1 percent that is not illusion does matter.

Behind all strategies lie the conditions of decision. Every decision is a choice among alternative images of the future present in the mind of the decision-maker. The images themselves (the "agenda" of choice) may be more or less realistic; they are created, however, by the learning experiences of the decision-maker, and these in turn are affected profoundly by the psychological makeup of the decision-maker, by the organizational milieu, and by the "image-climate" in which the decision-maker is placed. Once the agenda of choice is present in the mind of the decision-maker, the selection process by which one of the items or elements of the agenda is chosen emerges out of the valuation processes of the decision-maker. The agenda-formation and the valuation processes constantly interact; an alternative future, for instance, that may be quite realistic may be rejected because it is painful in terms of the values of the decision-maker, or one that is unrealistic may be accepted because it conforms to the values.

All thinking is at least partly wishful, and values always affect perceptions; up to a point this may not matter, but beyond a certain point this process becomes pathological. Out of these very complex processes finally emerges a value ordering of a specific agenda; the agenda item with the highest value is selected, and a decision is made. This is what the economists call "maximizing behavior", which simply says that all people do what they think is best at the time, a proposition so empty that it is almost impossible to deny. To put content into it we must examine the processes by which both agendas and value ordering are formed in the mind of a decision-maker. These processes are extremely complex and hard to discover.

A critical question, which is not easy even to formulate, is what makes a decision a "bad" decision. This is the problem of the evaluation and the pathology of decisions. In economics, there seem to be no bad decisions. Everybody chooses among a set of realistic alternations according to a structure of value orderings, beautifully rendered by indifference curves, about which there can be no further question. This type of analysis is a good place to begin. It is a poor place to end, however, simply because it is hard to deny the possibility of bad decisions, for everyone is conscious of having made them. The definition of a bad decision, however, is not easy. It is not merely a decision with unexpected consequences, for our agenda may have been faulty and a decision can still turn out well. Furthermore, almost all decisions have unexpected consequences, for all decisions are made about imaginary futures, not about real ones, and it is only for rather trival, very short-run decisions that the imagined futures turn out to be real. The definition of a bad decision in terms of subsequent regret has merit, though it runs into the difficulty that it does not distinguish between regret about unanticipated consequences and regret about the values that determined the original decision. Furthermore, although the minimizing of regret, as Marschak [1] has suggested, is a useful formal principle in dealing with decisionmaking under uncertainty (and all nontrivial decisions are under uncertainty!), it suffers from the formality of the general principle of maximizing behavior if we cannot specify a learning process by which regret about past decisions leads to less regret about present and future decisions.

An even more difficult question in the evaluation of decisions is that of decisions that other people regret—people, that is, who are not the decision-makers. Almost every decision affects other people besides the decision-maker, and these effects may be evaluated by the subject as being for the better or for the worse. The "power" of a decision-maker indeed may be defined by the number of other people who are affected by the decisions, or by the sum of the estimates of "betterness" or "worseness" that these decisions evoke in others, if these could be summed. The political process is the means by which joint estimates of the quality of powerful decisions are made over time. We may never reach consensus in these matters; nevertheless, there are processes—of election, of impeachment, even of revolution, and ultimately of the verdict of historians—by which we reach evaluations that are more than the private evaluations of individual persons and that are widely, even if not universally, shared.

DECISION-MAKING ENVIRONMENT

Another possible approach to the pathology of decisions is to look at the environment of the decision-maker to see if there is anything in this structure that is likely to lead to bad decisions rather than good ones. One does not have to be a determinist (which I am not) to argue that the decisionmaker's environment affects the probability that one decision will be made rather than another. This environment, as noted earlier, has a number of facets. There is first the internal psychological environment of the mind of the decision-maker—the genetic predispositions; the conscious and unconcious trauma from past experience; the general quality of disposition towards openness or secrecy, benevolence or malevolence, trust or mistrust, responsibility or irresponsibility; or any of the whole dictionaryful of dimensions of the human disposition. This internal environment is partly a biological artifact through the genetic and somatic constructions that build the body, but, it is mainly a social artifact through the information inputs that the individual has received from birth. It is n-dimensional to the point where exact descriptions becomes impossible, but without some attempt at describing it, psychohistory at least would be impossible. In systems that have a small number of powerful decision-makers, their internal environments cannot be neglected. Where there are large numbers of not very powerful decision-makers, something like a law of large numbers may come to the rescue, and their internal environments may be regarded as random disturbances that cancel out in the mass, as in the economic theory of perfect markets.

A second facet of the decision-maker's environment is the "image climate." This consists of the images of the world and of values present in the minds of the persons who constitute the culture within which the decision-maker has been formed and within which he or she operates. The image climate has a large effect on the learning processes by which the internal psychological environment is so largely formed. This accounts for the fact that within a given culture or subculture of interacting persons, there is convergence in the internal environments so that the members of such a culture become more alike.

A very important part of the image climate consists of the metaphors by which images of complex systems are presented to the mind and transmitted to other minds. The development of images of complex systems, such as the world economy, the international system, or even a large organization, is very difficult. The real world is more complex than any image that we can form of it; this must be so, because the human nervous system itself is part of the real world. All image-formation therefore involves abstraction, that is, a simplification of the structure of the real world to the point where our minds can contain it.

Abstraction takes two forms: models and metaphors. A model is a structure of specified parts, and relationships among the parts, that has something approaching a one-to-one relationship with the reality of which it is a model; a map is perhaps the simplest example; a mathematical model is a map-description in various abstract dimensions. A metaphor is a verbal mapping of the unfamiliar on the familiar; it says that something we do not know is "like" something that we do know. The construction and understanding of models is an advanced skill, largely confined to the scientific community. Metaphors can be understood even by the least sophisticated people and are the main stock in trade of preachers, politicians, lobbyists for both virtuous and mercenary causes, advertising men, prophets, persuaders, and visionaries. The danger is that while models may be more accurate, metaphors are more persuasive and often imply models that are not accurate. The sliced pie so beloved of distribution theorists, the balance of power, the domino theory, the eagle, the lion and the bear that are the totems of nations, the lifeboat ethic, the nuclear priesthood—all are metaphors and all imply models that may not be very accurate; nevertheless they have great powers of persuasion.

Fortunately, or perhaps for some people unfortunately, there is a real world. This constantly exerts an impact on the image climate, and even on metaphors, simply because of a fundamental asymmetry—that error has some chance of being detected, whereas truth has the real world on its side. Consequently, over the long pull our images of the world have a better chance of moving towards truth than they do of moving toward error, even though there are plenty of examples of the latter, thanks to the persuasive powers of human communication of all kinds in words, music, buildings, regalia, art, and all the other instruments of deception. But all persuasion, one hopes, will ultimately fall victim to truth, though it does seem to take an unconscionably long time.

Another facet of the decision-maker's environment, and a frequent source of bad decisions, is organizational structure. This particularly applies to powerful decision-makers, for power is largely a function of position in a hierarchical organizational structure. Even nonhierarchical structures, however, like a committee with a weak chairman, are capable of generating errors of agenda and of values, of which the supported "risky-shift" phenomenon [2] is a possible example. Accordingly to this phenomenon, a committee will make riskier decisions than individuals acting on their own, simply because everyone on the committee has an alibi and does not have to take full responsibility. Private decisions by single persons, the consequences of which impinge only on the decision-maker or his immediate circle, are probably the least subject to error and produce the most rapid feedback and learning process when they are in error. Unfortunately, this class of decision is denied to the powerful. In the mass, however, it may account for the important element of truth in Adam Smith's "invisible hand" metaphor, and the remarkable capacity of societies to correct, by innumerable small decisions of its ordinary members, for the follies, perversions, and extravagances of the powerful. This indeed is the great political virtue of the market mechanism, that it makes political decisions virtually unnecessary and relies on the cumulative impact of the small decisions of little people, which are much less likely to be in error than the large decisions of the great.

The decisions of powerful people, indeed, are almost doomed to be bad. Hierarchy corrupts communications, for a person rises in hierarchy by pleasing a superior, not by telling the truth. Consequently, the information reaching the top of a hierarchy has been filtered out at all the intermediate levels until it is likely to contain a great deal of error. Usually, it is only the bottom ranks of a hierarchy that are in direct touch with the real world—the foot soldiers, the parish priests, the students, the sales clerks. The powerful people at the top always have to rely on indirect and filtered information, which organizations are usually designed to corrupt. To some extent, this tendency for hierarchy to corrupt information can be offset by informal meetings, staff organization that bypasses the hierarchy, or the king's going out and wandering incognito through the slums, but even these devices tend themselves to become hierarchical. Nevertheless, no large organization is possible without hierarchy, simply because of the principle that whereas a small number of people can all communicate with each other, as the number rises the number of pairs of potential communicators increases almost exponentially, so that beyond a certain magic number (around seven) communications increasingly break down unless they are organized hierarchically. There must, however, be important other economies of scale in terms of division of labor, indivisibility of equipment, control of the market or the political environment, and so on, that offset the diseconomies of hierarachy; otherwise large organizations, like the dinosaur, would fall of their own weight and communications corruption. From the point of view of the probability of bad, or even fatal, decisions, however, each form of organization is likely to have an optimum scale, above which the probability of bad, size-reducing, or even catastrophic decisions rises sharply.

Another aspect of this problem is the mechanism by which powerful roles get filled. If there are only a few powerful roles in a society, some selective process is needed to distribute them at any one time among the persons of the population. These processes include hereditary roles as in a hereditary monarchy and roles filled by promotion, election, or chance. I have suggested that there is a "dismal theorem" of political science—that most of the skills enabling individuals to rise to power unfit them for exercising it. If this is true—and in the absence of strong random elements in the selection of powerful role occupants it is all too likely to be true, as in the famous Peter principle [3]—then the wide distribution of power is a certain safeguard against the almost inevitably bad decisions of the powerful. There is a certain dilemma here—wide distribution of power may protect against very bad decisions, at the cost of assuring there will be no exceptionally good ones. The cost of egalitarianism, especially in regard to power, may be a safe mediocrity.

EVALUATING STRATEGIES

If the evaluation of decisions is difficult, the evaluation of strategies seems even more difficult, because a strategy is precisely a decision about the evaluation of future decisons. Nevertheless, the "theory of bad decisions" that we have been outlining, while it is not the whole problem of strategy, is a very important part of it, for one of the major objectives of strategy is precisely to outline certain principles and organizational structures that will make for better decisions, rather than worse, in the future. Thus, a constitution is a political strategy designed to protect a society from bad decisions in the future, partly by organizational structures like "checks and balances" and also by the removal of certain potential alternatives from future political agendas. Much bad decision comes from a failure of agenda—too large agendas lead to information overload and a "clutching-at-straws" pattern of decision; too restricted agendas lead to a failure to perceive alternatives that would be valued more highly than any on the immediate menu. Some things should be removed from agendas—these are the "no-no's" of morality and law—and some should be deliberately added, like the environmental impact statements that force decision-makers to consider agendas they might otherwise have overlooked.

Perhaps the greatest problem of strategy is that it contemplates a much longer future than do most decisions, and the problem of the validity of images of the future becomes increasingly difficult—except under some unusual conditions of future convergence—as the time horizon expands and we look further and further into the future. The images of the future that form the agendas of decisions are obtained mainly by projecting the perceived patterns of the past, though often in very complex ways. We may use simple "celestial mechanics," as when we decide to jump out of the path of a moving vehicle that is bearing down on us. More often, we use complex combinations of images of space-time invariances, as when we decide to go to the post office and draw on our past experience that gives us an internal map of the town and knowledge of our capacity to follow a certain route to where we think the post office is located. All images of the future, however, involve some uncertainty; the approaching vehicle may accelerate or swerve, the post office may have moved, we may have an accident on the way, and so on. Uncertainty rises as we take longer time spans, mainly because the longer the time span we take, the larger becomes the probability that any uncertain event will happen *within* the time span. However, we cannot know when, and the "when" matters enormously in determining the actual pattern of the future. We are virtually certain that San Francisco will be destroyed by an earthquake in x years unless we find out how to lubricate faults, and that Washington will be destroyed by a nuclear weapon in y years unless we learn how to live at stable peace. We just do not know what x and y are, and there is no way in which we can know.

The specter of irreducible uncertainty broods over all models of the future, and strategy of all kinds must take account of this. Indeed, it is possible that a new source of bad decisions has been generated in recent years—the illusions of certainty that come with belief in sophisticated, computerized models of the future that do not take sufficient account of the irreducible uncertainties. The greater the uncertainty, the more important it becomes that, as new knowledge accumulates, strategy should involve liquidity, noncommitment, holding options open, and widening the agendas of future decisions. The most catastrophic situation can well be the illusion of certainty, in which case the strategy becomes to zero in on disaster. The Vietnam War may well have been an example of this.

APPLICATION TO ENERGY

How, then, do we apply these principles to the problems of energy strategy? We must start with some kind of image of the "real world" and the role of energy in it, with the full realization that any image that we present will have errors and uncertainties in it. What follows is my own image, offered for critique and possible testing.

The role of energy, both in the biosphere and in society, is dominated by the fact that energy is essential to any process of production. Production is a process by which a genotype becomes a phenotype, by which an egg becomes a chicken or a blueprint becomes a house. All processes of production start off with a structure of know-how that is the genotype. This know-how is able to capture energy for two major functions. One is to sustain the appropriate temperature at which the production processes go on, whether this is the 98.6° of the human body or the 1,000° of the potter's kiln. The other is to perform mechanical and chemical work by which materials are first selected, then transported, transformed, and rearranged into the improbable shapes of the phenotypes. From the point of view of the productive process, energy is not just ergs; it is ergs when and where and in the form in which they are wanted.

In the biosphere, production is "epigenesis," the process by which biological artifacts such as rabbits are made from fertilized eggs. In the social system, production is the process by which human artifacts, from the flint arrowhead to the space lab, are made from fertilized ideas. When these artifacts enter into exchange or gift relationships, they become commodities and enter into the field of economics. They become commodities, however, only because they have a larger social aspect as creators of utility. That is, they must be things people want, whether to satisfy biological needs such as food or to satisfy social desires for adornment, ceremony, and status. The production of all human artifacts, like that of biological artifacts, begins with an idea, combined with know-how, which is the genotype. If this is to be realized in production, it must be able to direct energy towards sustaining temperatures and transporting and transforming materials into the appropriate shapes. The absence of either energy or materials can limit the process of production. We see this on the moon, where evolution stopped about three and a half billion years ago, mainly because of the lack of an essential material, water, and only resumed sporadically in this decade as the result of the invasion of human beings and human artifacts from the earth. We see this limitation operating in paleolithic societies, where energy input into human processes of production consisted of little more than human muscles, with the result that only stone, skins, bone, and wood were available as materials and the ouptut of human artifacts was very small. With the ability to draw on accumulated energy reserves in the form of wood fires, the materials horizon expanded to include metals and pottery, and the quantity and variety of human artifacts increased by orders of magnitude.

Material objects are not the only human artifacts. Organizations likewise originate in some social genetic structure (an idea) and are formed through communication, persuasion, threat, exchange, and so on. They involve energy in bringing people together and in making the material artifacts that facilitate their operation, from temples and ritual objects to factories and machines. Individual human beings are partly biological artifacts made by biological processes from fertilized human eggs and partly social artifacts insofar as they acquire language, knowledge, skill, and behavior patterns from the other humans who surround them in the course of life. Persons, organizations, and material artifacts interact constantly in a complex social ecosystem and interact beyond this with the larger ecosystem that includes biological species and physical environments. Evolution—whether in the biosphere, the sociosphere, or both together—consists of this ecological interaction under conditions of constantly changing parameters: genetic mutation, climatic or physical changes, or social mutation. Human artifacts are part of this process of evolution; the automobile is just as much a species as a horse and just as "natural," just as much produced as a result of the evolutionary rise of know-how. The main difference between human and biological artifacts is that human artifacts are multiparental and can draw on the whole range of human know-how and social "genes," whereas biological artifacts can draw only on the gene pool of their own species. This is why social evolution is so rapid.

Human history from the very beginning has been characterized by something that can be called "development." In some of its aspects, this becomes "progress," which is a movement from states of the world evaluated as "worse" to those evaluated as "better." The process has also resulted in a very substantial expansion of the human "niche," with a fairly steady increase in the human population, barring a few wars and plagues, that has carried it now to over 4 billion. The process has resulted also in a continual expansion of the "sociomass"—the total mass of human artifacts—from a few flint knives and camp sites to cities, throughways, farms, factories, plantations, and so on. In addition there are unintended human artifacts like carbon dioxide in the atmosphere, pollution of air and waters, soil depletion, strip mines, and so on; most of these are perceived as "bads"—something that when increased makes things worse rather than better. Development, like the evolutionary process of which it is a part, is essentially a process in know-how, or genetic information structure. The know-how cannot be realized in the production of a product (phenotype) if there is a deficiency in energy or materials. Nevertheless, one of the remarkable things about human history is the way in which the expansion of know-how has constantly increased the availability both of energy and materials. As a result, the expansion of know-how has constantly pushed back the energy or materials frontiers that might limit it.

Furthermore, an expansion of the energy frontier seems to push back the materials frontier, and an expansion of the materials frontier often opens up new sources of energy or new ways of storing or transmitting energy. Thus, fire led to metals, metals led to tools, tools led to new materials and to coal, coal led to further expansion of metals, better tools led to oil and gas, oil and gas led to plastics, copper led eventually to electricity, and electricity led to aluminum and titanium, and so on in an extraordinary arabesque of interacting processes through time. Then the expansion of the energy and materials frontier feeds back in turn to the learning process, the essential increase in knowledge and know-how that is the central pattern of both biological evolution and human development. At some point in the expansion of energy and materials sources we were able to turn trees into paper, metals into type and later into computers; all facilitated the growth of human knowledge. Organizations likewise play a part in this complex feedback; material improvements like the telephone, the telegraph, and the typewriter made possible the "organizational revolution" after 1870—a massive reduction in the diseconomies of hierarchy and of scale that permitted the rise of large-scale organizations such as General Motors, the Pentagon, and the Soviet Union. Large organizations then create new methods of getting and using energy and materials that would be impossible without them, and so we go on, in a never-ending process of evolutionary disequilibrium.

In the last hundred or two hundred years, we have seen an enormous expansion of production of human artifacts, mainly because of rising knowledge, but also partly as a result of the discovery of fossile fuels, especially of gas and oil, and the discovery of new sources of materials. Petroleum and natural gas are extraordinarily cheap, convenient, storable, and transportable sources of energy. They are also an important source of new materials in the petrochemical industry. The discovery of electricity and its applications, which also took place in the nineteenth century, did not open up a new source of energy. It did, however, permit its transportation and especially its subdivision, facilitating its utilization in many convenient forms of light, power, and information transfer. Electricity, however, has a severe handicap in that it cannot be stored, especially in quantity, except at considerable expense. In addition, its transportation is both costly and clumsy.

Without fossil fuels, the modern world would not have come into existence. If the geological history of the earth had been such that there had been no coal, petroleum, or natural gas, the world today would still look very much as it did in the 1700's, though we probably would have radios and television powered pretty expensively by wood-fired power plants. We would almost certainly not have airplanes or automobiles, and the horse would still be producing high rates of infant mortality from fly-induced diarrhea.

We are now facing a "hundred years' crisis" in which petroleum and natural gas will be exhausted. Coal will last a little longer, but it is dirty, inconvenient, and dangerous. Existing nuclear technology will not last much longer than gas and oil, for uranium-235 will soon be exhausted. If we go to the breeder reactor, we can burn all the uranium, perhaps expanding the fuel supply by 5,000 years or more. If we go to the fusion, especially the deuterium reaction, we will expand the fuel supply to half a million years. All this is rather problematic. The direct use of solar energy on which we have always relied can undoubtedly be improved and expanded. Solar collectors and insulation can save half our heating and cooling bills, which account for 10 percent of our energy use. Solar power stations seem very expensive, dangerous, and hard to maintain. Nuclear reactors, especially the breeder, have a low probability of very large catastrophes, rather like dams. No substitute for oil and gas seems to be on the horizon. Most of the proposed substitutes produce only electricity, which is expensive, hard to transport, almost impossible to store in large quantities, and inefficient, except for the more delicate tasks. Paradoxically enough, it is the electricity produced by big power plants that makes the small beautiful.

OPTIMISTS AND PESSIMISTS

It is easy to get rather pessimistic about the outlook for the next hundred years. World per capita real income may even have peaked in 1973. It will almost certainly peak before the end of this century. The population explosion is probably increasing the number of poor people faster than the number of rich. Distributional strains in a world of declining per capita real income may become very large. The more complex a society becomes, the more vulnerable it may get. Development of the poor countries may be frustrated, in spite of the spread of know-how, if production is limited by lack of energy or materials.

In the rich countries, up until very recently we have simply taken energy for granted, because it has been granted. Consequently, we have not really had to have an energy policy or strategy. Public reaction to energy scarcities is hard to predict. The antinuclear movement is quite strong, especially among the virtuous middle class. On the other hand, when the chips are down, if the choice is having nuclear power or putting the lights out, nuclear power will probably win. There is a certain case for delaying it, especially in the United States, which could do without it for 25 years, simply because we have so much coal. The economic difference between coal and uranium-235 as a source of electricity is so small that it is within the error of estimate of the Gross National Product. Nuclear power, however, may be much more important for the development of the poor countries, where alternative fuels are available only at rapidly rising expense and where energy shortages would severely limit economic development. The consequences of this for the international system are not pleasant to contemplate in terms of nuclear weapons proliferation, but we may have to learn to live with it. Fortunately, at least 99 percent of human potential for doing harm is not realized, and even this percentage can be raised. We have enormous overkill capacity in table knives and in arsenic, with its half-life of forever.

Ideological considerations may determine whether energy is produced mainly by public or by private institutions. One is not sure that this makes much difference, as long as the institutions are large. We are shifting from a period in which the emphasis has been on supply to one in which conservation and improving the efficiency of the consumption of energy are likely to take on increasing importance. Conservation, however, is a strategy involving many small units (households for instance), and it is harder to do than the strategy of building large power plants. It can be done with suitable tax, price, and information systems. We do need to work on this, though we should not have any illusions that conservation will be popular. Waste, after all, is a rich man's good.

Cartels like OPEC can raise the prices of their product and divert economic rent to the owners of energy resources, but historically cartels have been a bit unstable. There is at least some probability, hard to estimate but not negligible, that OPEC will produce a temporary oil surplus, which will in turn produce strong temptations for the weaker members to break away and undercut the price. If this led to a collapse of the cartel—a process that has happened often in the past—and a return to competitive conditions in the world oil market, there would undoubtedly be shortrun gains, both for the very poor countries without oil and for the rich countries. Unless there were offsetting tax policies, however, this might mean that oil would stay cheap until the last drop, perhaps leading to a catastrophic crisis for which nobody had prepared.

The main justification for at least a modest longrun optimism in regard to all these future scarcities is that all price elasticities are likely to be much higher in the longer run than they are in short periods. A fourfold rise in the overall relative price of energy would have spectacular effects on increasing the total supply. Many sources of energy that now look rather exotic, simply because oil and gas have been so fantastically cheap, would burgeon into important industries under the stimulus of high energy prices. The fact that there are quite a number of different unexploited sources, especially of energy income directly or indirectly derived from the solar flux—wind, water, tides, and ocean temperatures—as well as geothermal sources suggests that the longrun elasticity of supply may be quite high.

The demand for energy likewise will probably have a much greater elasticity in the longer run than it does in the short run. A quadrupling of the average price of energy, for instance, would produce large changes in architectural design, in automobiles, in the use of solar heaters and panels, even in clothing to be worn at lower temperatures, in large numbers of industrial processes, and in the general commodity mix away from the high energy-using commodities. There are a great many things we have not had to do because energy has been so cheap, things that can be and will be done as energy becomes more expensive. The fact that energy cost still is a fairly small part of the total Gross

National Product means that even a quite substantial rise in its price, representing a roughly equal increase in the resources devoted to producing it, could be offset by a relatively small improvement in the efficiency of its use. Thus, if the energy industry constituted 5 percent of the GNP, with the rest being 95 percent, a quadrupling of the price of energy would raise the energy industry to 20 percent of the GNP, assuming perfectly inelastic demand; with the conservation that would be stimulated this rise might be only 15 percent. The rest of the economy would then be 85 percent of the GNP, and a general rise in resource efficiency of only (1-95/85), or 11.8 percent, would offset the 400 percent rise in the cost of energy.

While elasticity is a genuine source of longrun optimism, it would be unwise to deduce, as some of the more optimistic economists seem to think, that the elasticity of supply and demand will take care of all our problems. While it seems highly probable that at the present low price of energy, both supply and demand over the next generation or so will be highly elastic, we may then easily move into a price range where inelasticity sets in; if this is short of what would be required for continued world expansion of per capita real income, we could be in for a very rough time. Just to point out that the limits to growth are not absolute, and are modified by the elasticities of supply and demand, does not mean that they cannot become very real. On the supply side, the new technologies may simply not be enough to replace that vast elasticity of oil and gas supply that we have enjoyed so briefly. On the demand side, conservation is a one-shot operation; once it has been accomplished, demand may become very inelastic, and low-energy life styles may not prove to be appetizing. If we move into a price range in which both demand and supply are inelastic, however, a worsening of the supply situation (a movement of the supply curve to the left) can produce both very large changes in the relative price of energy and only small adjustments in the quantity. Sharp changes in the relative price structure, however, inevitably produce sharp redistributions of income, both among occupational groups and among income classes. These not only increase social and political tension, but are also likely to produce foolish policies in the effort to offset them.

APPLICATION OF PRINCIPLES

It is a curious fact that while economists have had a modest success in persuading political decision-makers to follow their advice in regard to employment and fiscal policy, they have had no success whatever in influencing price policy. The United States' reactions to the OPEC cartel are an almost classic example of what not to do. We have kept oil relatively cheap by quotas and a two-price policy. If we had put a substantial tariff on all imported oil, we would have captured some of the economic rent that now goes to the OPEC oil producers; if we had put an equivalent tax on domestic oil production, we would have encouraged conservation; and if we had allowed the price of oil to rise, we would have encouraged exploration. It is a sound general principle that if we have something that is plentiful now, but is going to be scarce later, there is a strong case for anticipating the future price rise and so produce an early stimulation of the long-run elasticities. The sensible policy is first to tax it heavily, which will raise the consumer price and encourage conservation, and perhaps in addition to subsidize new discoveries.

Can we then apply some of the principles of good and bad decisions outlined in the first part of this paper to the problem of energy strategy? Strategy involves thinking about how to improve the probability of good decisions and diminish the probability of bad ones. The problem of the psychology of the decision-maker we must neglect—not because it is unimportant, but because it is intractable to strategy. Possibly an improvement in parent education would yield us more sane adults in the next generation. For the most part, however, psychology must be included in the probabilistic part of our image of the future; just as we must include the probability of the hundred-year flood or the hundred-year nuclear disaster, so we must include the probability of the hundred-year lunatic in a powerful position. Hitler perhaps was a thousand-year lunatic. The great danger here is that we overlearn from the actual occurrence of improbable events and overestimate their probability after they have happened.

The problem of the image climate is likewise rather intractable to strategy, but, like psychology, it should be part of the background. We must be on the lookout, for instance, for the rise of taboos. A sense of cleanness or uncleanness is an important constituent of most people's images of the world. This is particularly important in the case of nuclear energy. Because of its dramatic use as a weapon against civilians (it is hard to visit the atomic museum in Hiroshima without being ashamed of the human race), nuclear energy had a curse on it from the start. In addition, it produces uncleanness in the shape of nuclear wastes, especially plutonium, whose radiations are deadly, invisible, and imperceptible except to priests with Geiger counters and other sacred objects—properties that they share with evil spirits. Plutonium is easily perceived as more unclean even than pigs, or liquor, or semen, or any of the other numerous objects that have driven mankind into taboos. Taboos on nuclear energy, therefore, are by no means out of the question. Taboos, furthermore, are very hard to deal with, because they involve an ineradicable mixture of rationality and irrationality. They may contribute to bad decisions; but they may also be a strategy for survival.

Decision-makers, especially powerful ones, rarely consider the impact of their decisions on the image climate. The decision, or absence of decision, by which the nuclear and military industries concluded that the problem of nuclear waste could be left to the future may have led to a change in the image climate very adverse to them. The most important element in the ongoing dynamics of the social system is the perceptions of legitimacy. Without internal legitimacy, morale—the sense that what one is doing is "okay"—no person or no organization can function. The withdrawal of external legitimacy, the perception on the part of other persons in the environment of an individual or an organization that what is going on is okay, makes the environment so unfavorable that it becomes extremely difficult to function, and the loss of external legitimacy often leads to the loss of internal legitimacy. These considerations should be in the background of any strategic decision. Deceit, the irresponsible exercise of power, secrecy, and many other factors can have powerful effects in eroding legitimacy.

Organization is fairly susceptible to strategic decision. Part of the perquisites of power is the ability to set up organizational structures. Government and any large organization can do this, and the question, therefore, of how organizational structures create bad decisions is highly relevant. One of the critical questions here is the scale of organization and the advantages or disadvantages of centralization and decentralization. There are no easy answers to this question; a great deal depends on the particular circumstances and environment and on the image climate of organizational decision-makers. The fact that there seems to be a centralization-decentralization cycle in most large organizations suggests that this is one of the insoluble problems—that everything we do is wrong, so we try a succession of wrong things one after the other.

Small is not necessarily beautiful nor big necessarily necessary. The small can be mean, and the large can be generous. On the other hand, a policy dominated by large organizations can easily miss the advantages of small scale. We should not overlook the household as a very significant unit in both energy consumption and possibly in production from wind, solar energy, and geothermal heat pumps. On the other hand, we are probably quite a long way from the idyllic utopia of household self-sufficiency. Large organizations will be with us for a long time, and we must learn to run them better. It is perhaps significant that Schumacher, [4] the author of "Small Is Beautiful," was an economist for a very large organization (the British Coal Board) and that his observations on how to run a large organization are very cogent!

There is no litmus paper for good strategies, though perhaps there is for very sour ones. The most one can hope for is that the agendas of strategists will be widened, and that the worst mistakes can be avoided. But even if that is all we can do, it is worth doing.

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General Energy Policy—II

(By Amory Lovins)

Readers who have not yet been exposed to "Energy Strategy: The Road Not Taken?" or "Soft Energy Paths" will find the major themes of those two unifying works smoothly summarized in the introductory paragraphs of next selection. The dichotemy between "hard" and "soft" technologies, the 50-year transition to the latter, and the special features and virtues of the soft path are detailed, though not documented.

On the other hand, readers unacquainted with the soft world created by Lovins may find it a little unusual. It is a world in which a utility can increase its profits by making unsecured loans to consumers for insulation and solar power rather than building power plants and selling electricity; in which "conversion of farm and forestry wastes" will supply the liquid fuels that comprise 34% of total energy needs; in which the spectrum of political economics extends from Marx to Keynes with only a side mention of the "abuses of pure mercantilism." In Lovins' world, the soft path is "cheaper, quicker, surer, and safer", while the hard path leads to a world that is "inequitable, hungry, anarchic, and tense."

The second selection by Lovins contains the technical back-up for his trend-setting article in Foreign Affairs. It was given at the same seminar at which the previous selection by Kenneth Boulding was presented.

[From No Man Apart—Mid September/October 1978]

How to Finance the Energy Transition

(By Amory Lovins)

The energy future will not be like the energy past. It entails a difficult transition away from reliance on oil and gas. But the nature of the transition depends on how we define the problem we're trying to solve. If we try simply to expand domestic supplies to meet projected total demands, we will continue our "hard" energy path—a policy of Strength Through Exhaustion that converts ever scarcer fossil and nuclear fuels to premium forms (fluids and electricity) in ever larger, more complex, more centralized plants.

But the costs of the hard path are intolerably high—in money, risk, even freedom—for it is inevitably centrist, autarchic, vulnerable, technocratic. It produces a world not of free enterprise and pluralistic choice but of subsidies, $100 billion bail-outs, oligopolies, regulation, nationalization, corporate statism—and perhaps Bertram Gross's "friendly fascism."

Suppose, instead, that we start by asking what tasks we want the energy for, and how we can do each task by supplying a minimum of energy (and other resources) in the way that is most effective for that task. We then find that we need new supplies of heat (58 percent of present United States needs for delivered energy) and liquid fuels (34 percent), not electricity (only 8 percent—far less than our current generating capacity). More power stations of any kind are not a rational response to this problem: They take too long to build, are far too costly, and provide a higher-quality form of energy than we can use economically.

SMOOTH TRANSITION

We can construct a smooth transition, over 50 years, to a virtually complete reliance on renewable energy sources by doing three things, starting now: using far more efficiently the energy we have; relying increasingly on "soft technologies"—diverse renewable sources (such as solar space and process heat, conversion of farm and forestry wastes, wind, and microhydroelectricity) that supply energy at the scale and of the quality we need—and meanwhile using fossil fuels briefly, cleanly, and sparingly in special "transitional technologies."

Such a "soft energy path" has its own political problems, but they are far more tractable than those of the hard path, and the soft path is also cheaper, quicker, surer, and safer—virtually anywhere in the world—assuming only presently available soft technologies and present life styles and social organization.

Since outlining this thesis in *Foreign Affiars* (October 1976) and in *Soft Energy Paths: Toward a Durable Peace* (Friends of the Earth/Ballinger, May 1977) I have responded to over 30 critiques (United States Senate, Small Business and Interior Committees, *Alternative*

Long-Range Energy Strategies, 2 vols., 1977/78), and had discussions with many people in the dozen-odd countries where soft-energy-path studies are underway. While much of the controversy has been technical ("Soft Energy Technologies," *Annual Review of Energy 3*, 1978, in press), a persistent political theme has also emerged: How can a free society implement a soft path without economic or institutional changes for which Americans may not be ready?

INEQUITABLE ACCESS

One important way of financing the transition to soft energy technologies will be outlined here in the broader context of energy prices and equity. Of course finance, while necessary, is not enough: we must also reform building codes, restrictive utility practices,conflicting incentives for landlords and tenants or for builders and buyers, and a long, messy list of other "institutional barriers." But inequitable access to capital may be the most fundamental obstacle to a smooth transition. The way we can overcome it illustrates how slight alterations in existing institutions can take us in new directions, turning conflict into cooperation and disparate problems into mutual advantages.

Many people who otherwise could and would use efficiency-improving devices and soft technologies lack the money to do so. At the same time, attempts to build centralized, hard-technology energy-supply systems are driving electric and gas utilities toward bankruptcy because those investments require too much capital and repay it too slowly. A logical approach to both problems is to transfer capital by loans from the second group to the first. This could make energy efficiency and soft technologies equitably available to all while making utilities financially healthy, thus directly benefiting both consumers and utilities. Capital transfers would simultaneously help to increase employment, clean up the environment, decrease inflation and interest rates, rapidly replace oil and gas, strengthen the dollar, and diminish nuclear proliferation.

Some utilities already loan money to consumers for insulating their homes (see *Business Week*, July 18, 1977) because insulation is a cheaper heat source than new power stations or new gas fields. Several states, such as Oregon (H.B. 2157, 1977), are mandating such loans. I too would have utilities—competing with heating-oil distributors, banks, insurance companies, the Federal Housing Administration, the Veterans' Administration, the Department of Housing and Urban Development, farm loan organizations, and other institutions—loan money to householders (and to others ranked according to how difficult it is for them to get cheap capital now) for fuel-saving investments.

EQUAL ACCESS

But two conditions should be added. First, the utilities should loan the money at the same rate of interest at which they would otherwise loan themselves money to build, say, a new power station. Second, borrowers should repay the loan (through their utility bills) at or below the rate at which the fuel-saving investment is expected to save them money. (The saving could be computed against the energy price the consumer would have paid if the utility had met his or her needs by building a new plant instead.) The first condition is meant to ensure that hard and soft technologies enjoy equal access to capital; the second, that loan repayments do not increase consumers' utility bills.

The utility would only loan the money. It should neither execute nor control the project, either directly or indirectly (for instance by setting equipment standards). The loan would not be added into the utility's rate base (its total investment on which it earns a regulated return): People who choose not to take part in capital transfers should not have to pay for those who do. The utility's profit, at the normally regulated rate, would be from interest on the principal loaned and would equal the return that the utility would otherwise have earned from a new plant. The utility's normal operations would continue—as would needed efforts at utility rate and structural reform.

The loan would have the same legal status and remedies for default as any other. It could be taken over by a new owner or tenant just like a utility hookup or a mortgage, and could be repaid prematurely without penalty and for an interest credit. Preferably the loan should be unsecured, since many who need it most have no collateral. Disconnection after due notice and hearing might be a last resort in case of brazen default.

CONSUMER BENEFITS

Capital transfers under this system would benefit both consumers and utilities. Consumers could heat their houses more cheaply than if they had not installed heat-saving or solar devices, yet without having to pay extra for the improvement. Second, insulation and solar heat would largely protect consumers from future rate hikes. Third, the fuel-saving investment would make the utility's cash flow more attractive (see below), would make the very costly new plants unnecessary, and would save the utility money and fuels by using present capacity more efficiently; these things all help to avoid rate hikes in the first place. (Solar heating in an energy-efficient building should have enough storage to need no back-up and hence should not make the utility's peak-load problem worse.)

Further, the lower capital requirements of soft versus hard technologies would mean lower interest rates and slower inflation. If utilities had to heat houses by building power plants and synthetic-gas plants to replace oil and gas, they would need so much capital that they would starve other sectors of the economy—leading to a net loss, directly and indirectly, of about 4,000 jobs per thousand-megawatt power station built. In contrast, conservation and soft technologies make more jobs per dollar invested, and leave more dollars available to create jobs elsewhere in the economy.

Utilities, while continuing to supply present lighting and appliance needs and perhaps eventually evolving into a distribution system similar to the telephone company (based largely on dispersed renewable sources), would avoid astronomical *new* investments to electrify space and water heating. Adding a completely solar heating system to a heat-conserving house requires about half as much capital as building a nuclear and heat-pump system to heat the same house, and one-fourth as much capital as building a nuclear system with resistance heaters (the kind now commonly used). Building solar heating for a whole neighborhood rather than for a single house would roughly double the capital saving. Heat conservation requires approximately one-sixth to one-thirtieth as much investment as a nuclear-powered heat-pump system; in new buildings, it can even reduce total construction costs.

ENEMY CO-OPTED

While a power station often takes 10 years to build and then 30 years more to repay its cost, conservation and solar investments take days or weeks to build and pay for themselves in about one to 10 years. If utilities invested in the latter systems rather than in the former, they could turn over their money faster and improve their effective rate of return, which they are sentimental about. Thus the transitional process, which they once saw as a threat, would become an opportunity—a better business to be in than building power stations—and a former enemy of soft technologies co-opted as a merchant banker for them. (Already, utilities in New Jersey and California that fought industrial cogeneration for years are scrambling to finance it because they can find neither money nor sites for conventional power stations that would be worse investments anyway.)

A healthier cash flow would improve utilities' bond ratings, reduce the rate of return they need to maintain those ratings, make their equity worth more, avoid dilution of existing stockholders' equity by new issues, and eliminate the rate hikes now commonly needed to make both debt and equity more attractive. Those rate hikes—a desperate measure by many utilities now at or near their legal limits on interest coverage, and borrowing in short-term paper just to pay dividends—might even be reversed.

Indeed, continuing to tie up huge blocks of capital for long construction periods would make utility cash flows fundamentally unstable. It takes so long to build a plant that by the time it is finished, the interim rate hikes needed to finance its construction (both directly and by keeping debt and equity marketable) may keep people from buying as much electicity as they were expected to buy. Revenues would then be too small to pay the fixed charges on the plant, requiring still higher prices, further reducing demand, and so on into the "spiral of impossibility" familiar from United States railroad finance. Diverting new investment into another business with short lead times and fast pay back—solar and conservation—would remove this instability.

KEEP UTILITIES SOLVENT

Thus capital transfers, which look like a Robin Hood act to consumers, don't hurt utilities. On the contrary, they keep utilities solvent without a bailout, and thus help to keep taxes down. (Your taxes now pay about 20 percent of the cost of every new power station; Senator Long wants to increase the nuclear subsidy to about 70 percent). The roughly two-thirds of typical rate hikes now needed to finance new plants would become superfluous. Rates would no longer zoom out of control and could even come down. And poor people would be as able as anyone else to afford insulation and solar heat.

Gus Speth, now a member of the President's Council on Environmental Quality, once proposed a refinement that could in practice help to substitute for pricing fuels at the cost of replacing them in the long run. He suggested that utilities should not get their Certificate of Public Necessity and Convenience to build a plant until they prove that they have exhausted the potential for energy efficiency improvements, peak-load management, and soft technologies that (1) would do the same jobs for consumers as the proposed plant, (2) compete with it economically, and (3) could have been financed by transfers of the capital allocated to build the plant. Only if these conditions were met would the plant economically and efficiently meet its customers' energy needs. Further to encourage realistic cost estimates and careful cost control, the amount the utility could add to its rate base, if it did build the plant, could be limited to the real plant cost it assumed in making the above comparison. This would keep utilities from simply passing on their uncontrolled cost overruns to consumers. It is a simple control mechanism that could make investments more socially responsible without requiring a stifling bureaucracy.

LARGER PATTERN

Capital transfers,whether or not linked with the utility certification test, are part of a larger pattern of efforts to meet people's energy needs fairly and at a reasonable cost. Yet economically efficient ways of allocating energy—or food or water or shelter—are always inequitable because some people start off rich and some poor, and rich people can always buy things that poor people cannot afford. A society worth living in will ensure that even its poorest members can afford the energy (and other things) needed for a decent life. But should we do this by fighting poverty or by subsidizing the innumerable things poor people need but cannot afford?

The latter approach means making energy (for example) artificially cheap—several times cheaper than what it costs us to replace it. But while this puts some energy in reach of the poor, it also means giving cheap energy to rich people. And if we want to use energy prices as an instrument of distributional equity, why not do the same for food, housing, education, travel, and everything else?

An alternative approach is to price energy (and other things) at levels reflecting actual costs and simultaneously to make poor people less poor by other means. Redistributing wealth or income, though it requires more political nerve, is a more direct, honest, and effective way to achieve social justice than tampering with prices in a futile attempt to make everything seem cheap enough to be afforded by people whom we haven't the compassion—or political will—to help directly.

Kidding ourselves, even in the name of fairness, into thinking energy is cheaper than it really is—long the cornerstone of United States energy policy—does not in fact yield cheap energy for anyone. It costs us dearly, if not immediately, then after the next election. Some of the cost is direct—the tens of billions of dollars in taxpayers subsidies that we pour into the energy system every year—but even greater costs arise from subtle inefficiencies and distortions throughout our society.

Suppose, for example, that we continue to pretend oil is very cheap. We will then probably continue to waste it and thus import more and more—bad news for our own independence and for other industrial countries more oil-dependent than we, and disastrous news for the third world. Then we must earn the money to pay for the oil. We do this mainly in three ways. We run down domestic stocks of commodities, which is inflationary. We export weapons, which is inflationary, destabilizing, and immoral. We export crops like wheat and soybeans, which inflates Midwestern land prices, raises our food prices, and makes us mine ground water in west Kansas (a cost that will soon catch up with us). We sell the wheat to the Soviets, enabling them to divert investment from agriculture into military activities. We must then raise our own military budget, which is inflationary—and which we must raise anyway to defend the sea lanes for oil tankers and to defend the Israelis from the arms we sold to the Arabs. (The easiest form of Middle Eastern arms control might be American roof insulation.)

Because the wheat and the soybeans are becoming more important to our oil balance of trade, we turn increasingly to more energy- and water- and capital-intensive chemical agribusiness. This damages the natural life-support systems, so we need more energy- and capital-intensive technical fixes like desalination and artificial fertilizers, and so on in a vicious circle. Meanwhile, back in the cities, we substitute "cheap" energy disproportionately for people, replacing human skills with energy-intensive machines. (This increases "labor productivity"—of people still working—and makes us call for more such machines to fuel the economic growth deemed necessary to employ the people disemployed by this very process.) This "structural" unemployment increases poverty and inequity, which increase alienation and crime (not to mention calls for cheaper energy). We then are hard-pressed to find money for crime control and health care since most of the money has already been spent on the energy sector, which is contributing to the unemployment and illness at which those social investments are aimed.

GARRISON STATE

At home we drift toward a garrison state, trying to protect the vulnerable energy systems from strikes, sabotage, and dissent. Abroad we ignore rational development goals, strengthen oil and uranium cartels, and vie in the competitive export of weapons, inflation, and reactors to the third world. These things encourage international distrust and domestic dissent, both entailing further suspicion and repression. As we burn the "cheap" fuels, we add to the air substances that could change climate and jeopardize world argiculture, especially in the third world monsoon belt and in the Midwestern breadbasket on which the third world increasingly depends for exported food. Our nuclear exports spread bombs all over. The world becomes more inequitable, hungry, anarchic, and tense.

These examples suggests that energy that *looks* cheap may actually be very expensive everywhere else in the economy—especially for poor people. Sooner or later, too, the high cost of replacing historically cheap fuels will come home to roost. In fact, we are *already* paying these costs: newly ordered nuclear electricity will cost, in heat equivalent, about seven times today's OPEC oil price.

Renewable sources now available are much cheaper than nuclear or synthetic-fuel systems for the same jobs—though many cost somewhat more than today's oil and gas.

Thus whether we use soft technologies or not, energy prices will rise because the fuels on which we have long relied are becoming scarcer and harder to get. The question is not *whether* prices will rise, but how fast, how predictably, how controllably, and who will get the money.

TWO INDUCEMENTS

There seem to be only two noncoercive ways to induce investors to save money by building soft technologies in time to replace the oil and gas but before the artificially cheapened average energy prices would make them profitable. The first way is to subsidize soft technologies so they can immediately "compete" with those average prices. But this subsidy to supply perpetuates an illusion of cheap energy (with all the indirect costs that implies) and merely transfers cost from our energy bills to our already swollen taxes.

The second method—which is much better economics—is to charge ourselves realistic prices, reflecting true replacement costs, for those no-longer-cheap fuels we are rapidly burning up. But how can we get our prices right? An across-the-board energy tax would be unfair and ineffective: We want only to raise the price of depletable fuels toward that of their long-term sustainable substitutes, the soft technologies. Further, an abruptly imposed fuel tax could be as disruptive as the sudden 1973–74 rise in OPEC oil price. Any tax should be introduced gradually, perhaps over a decade or more: It need only outpace rises in real wages and interest rates. But people must be able to anticipate future energy prices in today's investment decisions, so the tax should be phased in on an anticipatory schedule, avoiding the unpredictability and possible abruptness of deregulation. Such taxation does not raise prices simply to satisfy some masochistic prejudice that high prices are desirable. Rather, it anticipates and softens the inevitable, encouraging us to substitute soft technologies for oil in good time to minimize long-term energy prices—and ensuring that the money will be used in ways that remain under political control.

SEVERANCE ROYALTY

Many kinds of taxes on depletable fuels might serve this purpose. We now tend to use excise taxes on final fuels, such as gasoline; these require rebates for equity, so they have high administrative costs and lead to a swamp of intricate rules and exceptions. A much simpler approach would be a severance royalty—a uniform federal tax on all depletable fuels, charged according to their energy content, and levied as they come out of the ground or into the country. This tax would automatically become embodied in all goods and services according to their total direct and indirect energy content. Administration would be relatively easy because the machinery is already in place—the severance royalty is like a depletion allowance backwards—and because the royalty is simple and universal.

End-use excises hit the poor hardest, because poor people spend the largest fraction of income on direct energy purchases. But a tax imposed on primary fuels would not be significantly redistributive, because the fraction of income that Americans spend directly and indirectly on energy does not vary significantly with income (with a minor exception in the highest income bracket): Higher-income people simply spend a larger fraction of their energy budget on indirect energy embodied in goods and services, and the royalty would affect direct and indirect energy purchases equally. Further, revenues from a severance royalty could be rebated promptly to poor people or to especially hard-hit regions or groups, or used to finance efficiency improvements or soft technologies for those who need them most.

Nor would a severance royalty lead to the unbalancing side effects of more selective, special case fuel taxes, because it applies as much to uranium as to oil, gas, coal, oil shale, etc.: All are depletable fuels. It would not disturb the present cost disadvantage of nuclear power. Rather than reverse it would highlight the economic advantages of soft over hard technologies. Depletable fuel prices need not be made higher than soft-technology energy prices—at which virtually all hard technologies would still be very uncompetitive (to say nothing of their nasty side effects). We would then have achieved indefinitely stable energy prices lower than if we had done nothing. And while we might want some subsidies meanwhile to help conservation and soft technologies compete with the more heavily subsidized hard technologies, it is better economics not to subsidize any energy investments. Conservation and soft technologies can look after themselves on their inherent economic merits; only hard technologies cannot survive true competition.

Capital transfers are not a subsidy; they correct an imperfection in capital markets. But wider tax reform would also be helpful. For example, we should reform the policy that lets businessmen write off fuel as a business expense but forbids them from similarly deducting the capital costs of renewable systems; or reconsider the outmoded practice of taxing labor and subsidizing capital; or encourage durability by making excise taxes on consumer ephemerals (such as cars) inversely proportional to the length of the warranty. And while there is no natural monopoly on solar energy, abuses of market power are just as possible there as in agriculture, minerals, and industry generally, so vigorous antitrust enforcement and control of antisocial gigantism are important parts of a sound energy policy.

SALUTARY WARNING

Where I differ in the end from the doctrinaire views that pervade the energy debate—views ranging from Marxist to pure Keynesian—is that I neither regard free markets as real and perfect nor object to the principle of rewarding people who can sell something better and cheaper. While there is much talk of planning the solar transition, it is a salutary warning to would-be central planners that the Energy Research and Development Administration solar heating and cooling program was far outdistanced by a motley crew of individual entrepreneurs who did more in a year than ERDA through its massed (if misdirected) resources could do in five years. This country is simply too big and too diverse for central management to be more a part of the energy solution than part of the problem.

Indeed, among the greatest strengths of soft technologies is the fact that one person can understand them and make a basic contribution. There is, so far as we know, nothing in the universe quite so powerful as four billion minds wrapping around a problem. This is now beginning to happen, with extraordinary results. The distaste that some people profess for individual incentive should not make us reject the astonishing advances that human diversity and imaginativeness are already starting to offer. Nobody is wise enough to decide what will be the best solar technologies or how they should fit together: They may not even have been thought of yet, so fast is the field advancing. Thus, while the abuses of pure mercantilism are many, and must be checked by the more consistent use of the laws we are evolving for that purpose, socialism does not seem likely to solve, or even to help to solve, our energy problem. Whether we can respond to the energy challenge goes far deeper than our debates on socialism versus capitalism, or even Jeffersonianism versus Hamiltonianism: It depends rather on our values toward the earth and toward each other, not necessarily on the outward form of our political institutions. Profit and private enterprise can be fair; planning and nationalization can be inequitable—not to mention inefficient.

HELL WILL FREEZE OVER

Much though we need innumerable social reforms, oil depletion will not wait for them. If we make the resolution of our ideological disputes—capitalism versus socialism, price versus regulation, the future of the oil companies and indeed of our whole society—a prerequisite to addressing the energy problem, hell will freeze over first.

But a soft energy path can cut across these increasingly sterile arguments. If, for example, you are an economic traditionalist, you can build a solar collector because it is cheaper than competing sources; if you are a worker, you can build a solar collector because it gives more and better jobs than power plants; if a conservationist, because it is benign; if a social transformationalist, because it is autonomous. Yet it is still the same collector, and you need not agree, in advance or afterwards, about why you built it.

If we can use all the kinds of energy husbandry and renewable sources that people agree about, these will be enough. We can then dispense with the hard technologies that people don't agree about, because those will be superfluous.

Our tendency at times to focus the energy debate more and more on less and less reminds me of a woman who, while living in India, once called in a carpenter to fix a window frame. He followed her sketch too literally and botched the job. When she asked why he had not simply used his common sense, he drew himself up and replied with great dignity, "But common sense, Madam, is a gift of God. I had technical knowledge only."

"Technical knowledge only": perhaps a good epitaph for a civilization. But I think a tolerant common sense is alive, and living with the people, and will not be denied.

[Excerpt from "Future Strategies for Energy Development," Oak Ridge, Tenn., Oct. 20 and 21, 1976]

SCALE, CENTRALIZATION AND ELECTRIFICATION IN ENERGY SYSTEMS

(By Amory B. Lovins, London, England, Consultant physicist and British representative, Friends of the Earth, Inc.)

In what has come to seem an extended metaphor for energy strategy, Robert Frost once said:

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveler, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;
Then took the other, as just as fair,
And having perhaps the better claim,
Because it was grassy and wanted wear;
Though as for that the passing there
Had worn them really about the same,
And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way,
I doubted if I should ever come back.
I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I—
I took the one less traveled by,
And that has made all the difference.

Today, as the conventional road we gaze down bends ever more sharply into more obscure and brambly undergrowth, the sense of divergent choice of which Frost spoke is growing on many of us in the energy policy community. Three tangled issues—scale, centralization, and electrification—are emerging as key elements of that choice.

This symposium is apparently the first coherent and public attempt by "establishment" energy policy professionals to address these fundamental issues. This seems odd; after all, hundreds of billions of dollars have already been committed to large-scale central electrification on the assumption that its logic is obvious and unassailable. But it is the fate of all knowledge to begin as heresy and end as superstition (Huxley). For many analysts, overtaken by events that suddenly reversed traditional assumptions, the notion that scale issues are worth discussing has only lately emerged from heresy into respectability. Thence arises our challenge, and opportunity, to break new intellectual ground.

In this paper, I shall informally explore the implications of choice in scale, centralization, and electrification. If I seem at times to be presenting advocacy as well as analysis, it is because the results of the analysis have so impressed me, not because of preconceived ideological adherence to any particular position. Big high technologies probably have their place, and as a former high technologist I would not deny them that place. I merely conclude that it is a limited place and that they have long since saturated and overreached it.

I am likewise impressed by the way the arguments for matching energy supply in both scale and quality to end use fit naturally and powerfully into a coherent energy strategy. I have explored this thesis in a recent paper [1] that outlines and contrasts, not as precise recommendations but as a qualitative vehicle for ideas, two energy paths that the United States (and, by analogy, other countries) might follow over the next 50 years. The first, or "hard," path is high-energy, primary-supply-oriented, high-technology, centralized, increasingly electrified, and reliant chiefly on depletable resources (coal and uranium). The second, or "soft," path is high-efficiency (in end use), end-use-oriented, relatively low-technology and decentralized, electrified only where essential, based on renewable resources, and fission-free. I argue that though both paths entail difficult problems, the soft path offers major advantages in costs, rates, risks, equity, geopolitics (including control of nuclear proliferation), and domestic sociopolitics. Finally, I suggest that though each path is only indicative and embraces an infinite spectrum of variations on a theme, there is such a deep conceptual dichotomy between the two paths that the incremental resource and cultural commitments of the hard path, as "way leads on to way," are rapidly making a soft path less attainable in principle, and in practice, without prompt redirection, will soon foreclose it. This exclusivity makes choice urgent.

Since my earlier paper has already developed many of the arguments appropriate to this paper, I shall incorporate relevant sections here by cross-reference rather than repeating them. The relatively nontechnical treatment in my earlier paper will be complemented here with numbers, details, and qualifications that were omitted or excised there for reasons of both space and readership. The methodology used in this paper is discussed in Appendix I.

Underlying both papers, and indeed this symposium, is the contrast between two or more conflicting perceptions of what the energy problem "really" is. It will probably take at least another century of 20/20 hindsight to decide with universal certainty which perception(s) will have led to more appropriate actions. Indeed, I am uncertain whether our attempts to influence the future are likely to have the effect we intend rather than the opposite one—though that doesn't mean we shouldn't try. Accordingly, however persuasive or appealing a particular view of the world may seem to each of us, it is premature to conclude that other views are "wrong." We must accept them at face value as a basis for discussion in good faith, appreciating that identical facts seen by different people can give rise to completely different perceptions and to different views of what facts are important. Some relevant facts as I see them are set out elsewhere. [1–4] As a basis for mutual understanding, however, it may be useful for me to summarize a few of my underlying opinions—not on every aspect of social philosophy, geopolitics, ethics, international development, peace, and other parts of the whole universe of perceptions that must support any consistent view of our energy future but, at least on a few basic values. Briefly, then, I think that:

(1) We are more endangered by too much energy too soon than by too little too late, for we understand too little the wise use of power.

(2) Through technical changes only, the United States can roughly double its end-use energy efficiency [1] by about the turn of the century,

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[1] People who believe that the Cooper-Weinberg projections [6] of demographic and economic growth are too low should reflect that improvements in energy efficiency occur most rapidly at the margin. The more new houses, machines, etc., are built, the faster the old, less energy-efficient stocks can be diluted or replaced. Thus people who postulate rapid population and economic growth and correspondingly rapid energy growth are trying to have it both ways.

then roughly redouble it over the ensuing half-century or so (the pattern implied by Figure 2 of reference 1 being by no means the lowest that might be realistically considered).[2]

(3) Through voluntary value and structural changes only, we could do approximately the same thing, with at least equal benefits to equity, liberty, comfort, employment, happiness, and national capacity to cope with domestic and world problems.

(4) Many of these value changes are desirable or essential, and many are already occurring rapidly (Harman's transformationalist theory [5] has considerable merit).

(5) In practice, we can and should use some combination of technical and structural changes to increase end-use efficiency at least three- or four-fold over the next three or four generations.

(6) Over that period our concepts of social welfare are likely to change profoundly, and using Gross National Product (GNP) to measure it will savor of a category mistake.

(7) Accordingly, the energy problem is not how to expand supplies to meet the postulated extrapolative needs of a dynamic society, but rather how to accomplish social goals elegantly with a minimum of energy and effort, meanwhile taking care to preserve a social fabric in which diverse values can thrive.

(8) The technical, economic, and social problems of fission technology [3,7] are so intractable, and technical efforts to palliate those problems are politically so dangerous, that we should abandon the technology with due deliberate speed.

(9) Many other energy technologies [1,2,4] are exceedingly unattractive and should be developed and deployed sparingly or not at all—for example nuclear fusion, large coal-fired power stations and coal-conversion plants, many current coal-mining technologies, urban-sited liquefied natural gas terminals, much Arctic petroleum extraction, most "unconventional" hydrocarbons, and many "exotic" large-scale solar technologies such as solar satellites and monocultural biomass plantations.

(10) Ordinary people are qualified and responsible to make these and other energy choices through the democratic political process, and on the social and ethical issues central to such choices the opinion of any technical expert is entitled to no special weight.

(11) Technical experts contributing to public discussion of such choices should call special attention to uncertainties and professional disagreements, lest they give the impression that disputed questions are actually resolved.

(12) Issues of material growth are inseparable from the more important issues of distributional equity, both within and among nations—indeed, high growth in overdeveloped countries is inimical to development in poor countries.

(13) The self-reliant ecodevelopment concepts inherent in the New Economic Order approach—and inconsistent with hard energy technologies—are commendable and practicable, provided we overcome the danger of not being imaginative enough.

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[2] Many people still do not know the difference between improved end-use efficiency and curtailment of end-use functions. For example, Americans for Energy Independence, who advocate "maximum feasible production of all forms of energy," are reportedly preparing a conservation program consisting largely of curtailment—presumably to induce the public to identify conservation with the taste of cod-liver oil.

(14) Though the potential for growth in the social, cultural, and spiritual spheres is unlimited, resource-crunching material growth is inherently limited, and, in countries as affluent as the United States, should be not merely stabilized but returned to sustainable levels at which the net marginal utility of economic activity is clearly positive.

(15) People are more important than goods; hence energy, technology, and the economy are means, not ends; hence economic rationality is a narrow and often defective test of the wisdom of broad social choices.

(16) Though humanity and human institutions are not perfectable, legitimacy and the nearest we can get to wisdom both flow, as Jefferson believed, from the people.

(17) Pragmatic Hamiltonian concepts of central governance by a cynical elite are unworthy of our people and are ultimately tyrannical.

(18) Since sustainability is more important than the momentary advantage of any generation or group, long-term discount rates should be zero or even slightly negative, reinforcing a frugal (though not penurious) ethic of husbanding.

(19) Nature knows best, whereas we know little of the natural systems and cycles on which we depend; hence we must take care to preserve safety margins whose importance we do not yet understand, and to design for resilience and flexibility.[3]

(20) The national interests of the United States lie less in traditional geopolitical balancing acts than in striving to attain a just and equitable, therefore peaceful, world order, even at the expense of temporary commercial advantage.

Perhaps these elements of a credo will help readers to see what lies behind my views on energy strategy, just as other perceptions lie behind different views. I must again stress, however, that my views on energy and on other matters coevolve; neither can be said to be derived from, or reshaped to justify, the other.

One further introductory comment. I consider the structural, sociopolitical, and value implications of energy paths to be paramount both in theoretical importance and in practical impact on political acceptability. These implications are highlighted by the soft/hard dichotomy [1], which is definitive and crucial. Whether an energy path is high or low is derivative and less interesting. In energy strategy as in system dynamics, the *structure* of the system is far more important to its behavior than the exact values assumed for its coefficients.

Some commentators seem to have missed this point. Alvin Weinberg, for example, has proposed that a strongly nuclear-electric future, modified by "technical fixes" (such as clustered and perhaps underground siting, and administration by a technological priesthood socially isolated from the public), should be acceptable to me and to other nuclear critics if at the same time the demand for energy is greatly reduced by increasing end-use efficiency. Let us suppose—though I do not think it is true—that the problems of fission are amenable to such technical fixes without untoward social side effects. Let us further suppose that a strong-conservation-plus-strong-nuclear policy is internally consistent, though I doubt, as a matter of empirical sociology, that these two constituencies overlap much. Yet even on these heroic assumptions, the argument misses the point: that an essentially nuclear-electric future, even scaled down, *is still a hard energy path* [1] in structure and in sociopolitical implications. The structural effects of pervasive centralized electrification matter far more than whether its enormous extent is doubled or halved. Thus the arbitrary assumption [6] that even a nuclear moratorium would still mean a half-electric economy by about 2000—i.e., that it only means building big fossil-fueled power stations instead of big nuclear power stations—has kept Alvin Weinberg and his group at the Institute for Energy Analysis from addressing the most interesting policy questions. The breadth of the soft-path concepts, whose attractions [1] seem to me a key element in the nuclear debate, requires far more than monovariate analysis. Suppressing these concepts by an invariant ex cathedra assumption of centralized electrification reminds me of the popular lapel button that says:

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[3] Since, as Niels Bohr remarked, "It is difficult to make predictions, especially about the future."

Technology is the answer! (But what was the question?)

I sympathize with the difficulties that the Institute for Energy Analysis faces in addressing the deeper and harder questions on which I hope to make a modest start here, for the issues of scale, centralization, and electrification are so inextricably intertwined that it is not clear how to grasp any one of them. The economies available at small scale, for example, are in principle separable from the issue of thermodynamic matching of sources to end-use needs. Yet in practice, electrification of the type currently proposed tends to be centralized and large-scale, thus adding structural issues to those of thermodynamic appropriateness and inherent capital intensity. [1] In this paper, I have been unable to treat the three issues separately for more than a few paragraphs at a time. I shall instead outline some basic concepts of scale and energy quality, then amplify my earlier summary comments [1] on comparative whole-system costs, and finally address the crucial sociopolitical and value problems of soft vs. hard energy paths.

SCALE

Since energy is but a means to social ends, and since energy is useful only insofar as it performs specific tasks relevant to those ends, anyone seeking to perform tasks with the least possible energy and trouble should start with an inventory of tasks. Specifically, to design a rational energy system, one should first assess the unit scale, type, quality, and degree of geographical clustering of energy needs as a function of space and time. Such an elementary data base does not exist today anywhere in the world. So far as I know, no country even has a usable inventory of the scale of individual end-use energy needs. One must instead fall back on naive order-of-magnitude observations—simple but instructive.

For example, the heating load of houses is typically measured in thousands of watts (W); the peak power output of a car is of order 100,000 W; the total input to one of our society's largest integrated industrial facilities—certain primary metals and isotope-enrichment plants—is on the order of 1,000 megawatts (MW) with current designs (which might arguably be different were it not for large dams and power grids). With isolated exceptions, mainly pathological cases associated with large dams or coal complexes, virtually all our end-use systems are probably smaller than about 100 MW (the inefficient

World Trade Center is wired for a peak electrical load of 80 MW), and great many—probably the majority—are clustered in domestic, commercial, and industrial units smaller than about 1 MW. Most of the end-use devices important to our daily lives require to order 0.1 to 1,000 W and are clustered within living or working units requiring of order 1,000 to 100,000 W. Most production processes of practical interest can be (and long have been) carried out in units of roughly that scale.

Thus it is not obvious prima facie that energy must be converted in blocks of the order of hundreds of thousands to tens of thousands of megawatts. The arguments usually articulated for such large-scale include reduced unit capital cost, increased reliability, central high-volume delivery of primary fuel, localization and hence simplified management of residuals and other side effects, ability to use and finance the best high technologies available, ease of attracting and supporting the specialized maintenance cadre that giant systems require, ease of substituting primary fuels without retrofitting numerous small conversion systems, and convenience for the end user (who need merely pay for the delivered energy he purchases as a service, not involve himself in the details of its conversion). These contentions are not devoid of merit. Big systems do have some real advantages—though advantages are often subjective, and one person's benefit can be another's cost. But I shall suggest below that many of the advantages claimed for large-scale may be doubtful, illusory, tautological, or outweighed by less tangible and less quantifiable but perhaps more important disadvantages and diseconomies.

Some diseconomies of large scale are starting to be widely appreciated. For example, it is now well known that large electrical components, notably turbogenerators, often lose in reliability—hence in contributions to grid operating costs, standby capacity costs, grid instability, and lost revenues—what their size gains in unit capital cost. These effects are so common that there is mounting evidence [8] that most types of power stations can have lower busbar costs in sizes of the order of hundreds rather than of thousands of megawatts. Dispersed generation near load centers is well known to improve system integration and stability. According to one recent study [9]

> For one small system, and with assumptions that we believe are realistic, it was found that kW of dispersed generation was equivalent from the standpoint of reserve requiremnts to 2.5 kW of central generation. The reliability of supply within the network was determined by means of an index related to the LOLP [loss-of-load probability]. The reason why the dispersed device can be so effective is that it protects the load in its vicinity against generation as well as transmission and distribution outages.

Thus the "dispersion credit" traditionally assigend to local supply—e.g., from battery banks or fuel cells associated with distribution facilities—may be far too low, since it reflects only the cost, on the order of $100/kilowatt (kW), of saved transmission facilities. Unfortunately, publication of a study by the Electric Power Research Institute with this conclusion has been suspended, so few recent data are available. The extreme capital intensity of all electrical facilities offers ample reason to explore carefully the reliability implications of more centralization. The classical literature of this subject seems to me sketchy and unpersuasive and its quantification primitive.

A further diseconomy of large scale is so obvious that it is often forgotten. The past few decades' military experience in Europe and

Indochina has taught us that central energy systems reliant on a few large facilities are far more vulnerable, and harder to restore when damaged, than dispersed systems.[4] This concept has led to design criteria used today in Israel and, I am told, the People's Republic of China.

Small energy systems suited to particular niches can mimic the strategy of ecosystem development, adapting and hybridizing in constant coevolution with a broad front of technical and social change. Large systems tend to evolve more linearly like single specialized species (dinosaurs?) with less genotypic diversity and greater phenotypic fragility. Large systems also accrete costly, specialized infrastructure that strongly influences future lines of development. Thus unamortized natural-gas pipelines, the third largest U.S. industry, provide a strong incentive to make synthetic pipeline-quality gas even at a price an order of magnitude higher; building a grid dependent 1,000-MW blocks of electricity discourages a future shift to smaller-scale or reduced electrification. Small systems, in contrast, tend to depend more on infrastructure installed at the point of end use, thus increasing the user's ability to adapt. For example, resistive heaters and electric heat pumps are not very adaptable, so an all-electric house is hard to heat except with electricity from some source. A domestic or district heating system based on circulating hot water, however, can use virtually any heat source at any scale without significant change to the domestic plumbing, adapting to as wide a range as solar collectors, solar/heat-pump hybrids, and combined-heat-and-power district stations. Thus if a transitional technology such as coal-fired fluidized-bed gas turbines with district heating [1] is deployed first in those urban areas where solar backfits will be slowest and least convenient, with district heating clustered in holding tanks of neighborhood scale, then that interim heat distribution system (coupled to existing domestic plumbing) can be adapted later to whatever soft source of heat becomes available in each neighborhood. Infrastructure at or near the point of end use can be designed for this sort of piggybacking, whereas large-scale distribution infrastructure enables one only to choose one or another kind of enormous central power station, gas plant, etc.

Large-scale systems already in place (not at the margin) can be useful transitional tools on a regional scale. For example, my studies of a soft energy path for Denmark [3] came to conclusions similar to Sørensen's, [10] though I used more organic conversion, less electricity, and no hydrogen. But the 50-to-75-year transition, even though no more awkward than under present policy, could be made far easier within a Scandinavian hegemony that shared surplus Norwegian hydroelectricity in return for food and other exports from Denmark and Sweden. Current studies within the European Economic Community [11] may reveal scope for other such regional policies—not that they are an argument for building more big systems than we have now.

I have already outlined [1] some of the potential technical and economic advantages of small scale: [12]

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[4] My statement [1] that soft technologies are not militarily useful referred to direct applications, not reduced vulnerability. In the latter sense they are extremely useful.

(1) Virtual elimination of the capital costs, operation and maintenance costs, and losses of the distribution infra-structure (see below).

(2) Scope for greatly reducing capital cost by mass production if desired.

(3) Elimination of direct diseconomies of scale, such as the need for spinning reserve on electrical grids.[5]

(4) Major reductions in indirect diseconomies of scale that arises from the long lead times of large systems: for example, exposure to interest and escalation during construction, to mistimed demand forecasts, and to wage pressures by a large number of strongly unionized crafts well aware (as in the Trans-Alaska Pipeline project) of the high cost of delay.

The very conditions that make the indirect diseconomies of large scale important make them hard to quantify. Nonetheless, some utility managers are realizing that interest, escalation, delays owing to greater complexity, and the effects of forecasting errors can make a single large plant of capacity *C* more costly than *N* smaller plants of capacity *C*/*N* with shorter lead times. It is an inherent engineering feature of soft technologies,[6] moreover, that their lead times are qualitatively shorter than those of conventional big systems. [1] Whether in development, demonstration, or deployment, a small and technically simple system such as a rooftop solar collector, requiring months and thousands of dollars, is quicker and has lower indirect costs than one such as a fast breeder reactor, requiring several stages of scaling-up and billions of dollars (and perhaps a decade) per stage. Even a relatively adventurous soft or semisoft technology, such as a large wind machine, requires less than 2 years to design and build from scratch. The complete process for large solar heating systems today can be less than 2 months.

An intangible but important advantage of small scale is its scope for reducing public alienation (hence opposition, costly in these escalatory times) by building a greater sense of participation. A giant energy facility is arcane, remote, unfamiliar, and so impressive as to be threatening. A small system has an obvious relevance to everyday life because it is both physically and conceptually closer to the end-use task. For example, the New Alchemy Institute's biologically sophisticated Ark project in Prince Edward Island has taken an impressive hold on the popular imagination all over the Province. It has tapped a hitherto unsuspected reservoir of intelligent interest and initiative, not only because it is easy to visit and understand,[7] but also because it is a farm that grows fish and tomatoes—a readily assimilated extension of everyday agrarian life. It makes more sense and seems more relevant to the Islanders than a CANDU in New Brunswick or Ontario, just as Biharis could justifiably suppose that having methane digesters and solar cookers in their villages would help them more directly than building more reactors in California.

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[5] Trying to judge the true cost of prompt spinning reserve leads one into dense definitional thickets; but it is a big number, and someone must pay for it.

[6] As noted elsewhere [1] "soft" is not a wholly satisfactory term, though already widely used. Some alternatives, like "supple" (vs. "brittle") or "pluralistic" (vs. "monolithic"), are not definitive enough. "Convivial" (vs. "radical-monopolistic" [13]) is, alas, too obscure. "Mature"—i.e., surprise-free and straightforward rather than speculatively straining technology to and beyond its limits—is apt, but some people may reverse Commoner's original sense. [14] "Proven" (vs. "unproven") likewise shifts meaning with speaker. Perhaps the best term, "appropriate," which comes to us from modern development economics, lacks concreteness for some people and is perhaps broader in application than we want. Terms stressing only smallness, renewability, etc. are of course too narrow to embrace the five defining characteristics of "soft technology." [1] All suggestions for a better term will be welcome.

[7] And makes manifest our interdependence with the natural world, reintegrating us into it and enhancing our sense of wholeness: a special strength of combined innovation in energy and agricultural systems.

In short, because small, soft technologies [1] use equitably distributed natural energies to meet perceived human needs directly and comprehensibly, rather than being oriented toward abstract economic services for remote and anonymous consumers, they are, in Illich's sense, [13] "convivial." Of course, there may be Economic People who want as little as possible to do with their own life-support systems, and are content to pay their utility bills without a murmur, gobble precooked plastic food as the television exhorts, and eagerly turn every aspect of life into a prepackaged component of GNP. Yet I do not seem to meet such people. It seems to me rather that most people want to understand their own systems and feel responsible for their own destinies, not be mere economic cogs. That is why, for example, even the most narrowly materialistic people complain about impersonal and shoddy "service," [8] arrogantly paternalistic utilities, incompetent auto mechanics, outrageous bills for simple repairs, and petty bureaucracy. That is why many increasingly cherish the small corner shop, feel guilty rather than satisfied at eating hamburgers that are a by-product of petro-chemicals manufacture, and try to persuade the dentist to explain exactly what is wrong with that tooth. That is why creative personal activities of all kinds are flourishing—from gardening and canning to weaving and do-it-yourself carpentry (and, arguably, citizens' band radio). Perhaps I must meet a skewed sample of people, but I do not think so. When typical all-American slurbians tell me with obvious pride that they have just changed their own fuses, made their own preserves from their own fruit, sewed their own clothes, or insulated their own attics, I sense that they have done these things not only because it pays but because it is satisfying and fulfilling. They are proud to recount it because it symbolizes a small triumph of quality over mediocrity and of individualism over the System. The emotions that such involvement releases—a psychological aspect of scale—are powerful, lasting, and contagious. They must not be ignored.

Of course this striving for personal participation and understanding occurs often at a neighborhood or community level (though seldom at a city or regional one, since by definition one cannot then know one's neighbors). There are often good reasons to share even simple energy systems among, say 10 to 1,000 people. For example, neighborhood solar heating systems (for individual or cluster housing) can clearly offer substantial economies over single-house systems through freer collector siting and configuration, reduced craftwork, reduced surface-to-volume ratio in storage tanks, more favorable ratio of variable to fixed costs, and perhaps even a bit of user diversity (different people using, say, hot water at different times, though this would be a very small term). Many transitional energy systems, too, might have to be on a substantial scale: It is even too early to rule out entirely the possibility of fairly large-scale coal conversion to make industrial gas for a transitional ring-main in the Midwest, until fluidized-bed backfits (particularly for industrial packaged boilers, with or without cogeneration) can take up the slack. [1] Most such boiler backfits will also have to match existing industrial scale, whether it is optimal in the long run or not. [12] But all such transitional technologies, unlike those now planned, would be designed at appropriate scale so that they and their infrastructure can later mesh with smaller, softer technologies. Thus the scale issues in the soft-hard debate are relevant to larger transitional systems too.

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[8] A recent survey showed 40 percent of consumer purchases resulting in complaints (mostly in vain). The costs of correction, if any, were of course passed through to the consumer via Galbraith's "costs-plus economy," and the only incentive to do better—a powerful one, but very slow—would be public withdrawal of legitimacy from the institutions responsible.

ENERGY QUALITY

I am not aware of any definitive or detailed survey of the thermodynamic structure of end use in any country. But to obtain round numbers for the United States, we can start with the Ross and Williams revision [15] for 1973 of the somewhat problematical Stanford Research Institute data base [16] for 1968, as shown in Table 1.

TABLE 1.—U.S. PRIMARY ENERGY CONSUMPTION BY END USE, 1973 (QUADS, OR 10^{15} BTU/YEAR)

Sector	Direct fuel	Electricity	Total fuel
Residential	7.89	1.97	14.07
Space heat	6.16	.32	7.19
Water heat	1.26	.28	2.13
Air-conditioning		.32	1.00
Refrigeration		.38	1.18
Cooking	.38	.08	.63
Lighting		.26	.82
Clothes drying	.09	.08	.34
Other electrical		.25	.78
Commercial	6.65	1.74	12.06
Space heat	4.28		4.28
Water heat	.61		.61
Air-conditioning	.35	.41	1.63
Refrigeration		.28	.87
Cooking	.15		.15
Lighting		1.05	3.26
Asphalt and road oil	1.26		1.26
Industrial	21.44	2.96	29.65
Process steam	10.54		10.54
Electricity production	.33		.33
Direct heat	6.58	.18	7.09
Electric drive		2.34	6.48
Electrolysis		.34	.94
Other electrical		.10	.28
Feedstocks	3.99		3.99
Transportation	18.91	.02	18.96
Automobiles	9.81		9.81
Trucks	3.90		3.90
Aircraft	1.29		1.29
Rail	.58	.02	.63
Pipelines	1.81		1.81
Ships	.26		.26
Buses	.16		.16
Other	1.10		1.10
Grand total	54.89	6.69	74.74
(Percent of grand total)	(73)	(9)	(100)
Grand total excluding pertrochemical feedstocks, reductant coke, asphalt, and road oil	49.64	6.69	69.49
(Percent of grand total so modified)	(71)	(10)	(100)

Source: M. Ross and R.H. Williams, "Assessing the Potential for Fuel Conservation," Institute for Public Policy Alternatives, State University of New York at Albany, July 1975.

If we ignore fuels used as materials and consider only the separable problem of fuels used for their energy content, we can now construct an illustrative table of the approximate distribution of end-use enthalpy according to the type of work to be done as shown in Table 2. Note that conservation laws are satisfied: The horizontal sum of the grand total row is 69.49×10^{15} British thermal units (BTU) or 69.49 quads, which is the primary energy use (as fuels) shown in Table 1. The upper row of percentages at the bottom of Table 2 is equivalent, in round numbers, to that given on page 78 of reference 1. There the obligatorily electrical component is disaggregated into roughly half industrial electric drive and half other applications. The temperature distribution of heat requirements mentioned there pessimistically assumes classification by terminal temperature, not total temperature change (see Appendix II).

What does Table 2 mean? Of course it takes no account of end-use effectiveness or efficiency—of how much of a stove's heat, or the primary energy used to produce it, gets into the pot, or of the ability of 0.32 quads of electricity applied to residential air conditioners to move about 0.61 quads of unwanted heat [17] into the volume of air partly cooled by a neighbor's air conditioner. But the coefficient of performance (COP) attainable from electrically driven heat pumps such as refrigerators may not be as important as we would like to suppose: Heat pumps can be driven by any source of mechanical work (including wind-hydraulic drive), and refrigeration, as Robert Williams has pointed out, can be advantageously integrated into the heating and cooling system of a house (solar or otherwise) rather than restricted to a special plug-in appliance. Even the undoubted efficiency of electricity for driving motors pales a bit when we recall that mechanical work in fixed devices is about 7 percent of all end use; that fossil fuels are also very high-grade forms of energy and are often used at very respectable First Law efficiencies; and that the First Law efficiency of the electric motors studied by Goldstein and Rosenfeld [18] has fallen from 71 percent to 49 percent for a single manufacturer since 1940 (and to 30 percent for another manufacturer).

TABLE 2.—U,S. DELIVERIES OF ENTHALPY BY END USE, 1973 (QUADS, OR 10^{15} BTU/YEAR)

Sector	Heating and cooling		Portable liquids	Miscellaneous mechanical work	Obligatorily electrical	Lost at power stations
	ΔT<100°C	ΔT≧100°C				
Residential	8.72	0.62			0.52	4.21
Space heat	6.48					0.71
Water heat	1.54					0.59
Air-conditioning	0.32					0.68
Refrigeration	0.38					0.80
Cooking		0.46				0.17
Lighting					0.26	0.56
Clothes drying		1.16			[1,2] 0.01	0.17
Other electrical					[2] 0.25	0.53
Commercial	5.93	0.15			1.05	3.67
Space heat	4.28					
Water heat	0.61					
Air-conditioning	0.76					0.87
Refrigeration	0.28					0.59
Cooking		0.15				
Lighting					1.05	2.21
Industrial	4.84	12.46			2.78	5.58
Process heat	[3] 4.84	[3] 12.46				0.33
Electric drive					[2] 2.34	1.14
Electrolysis and other electrical					0.44	0.33
Transportation			17.10	1.81	0.02	0.03
Autos, trucks, buses, air, ships			15.42			
Rail			0.58		0.02	0.03
Pipelines				1.81		
Other			1.10			
Grand total	19.49	13.23	17.10	1.81	4.37	13.49
(Percent of 56.33 quads [5])	(35)	(23)	(30)	(3)	(8)	
(Percent of 69.49 quads)	(28)	(19)	(25)	(3)	(6)	(19)

[1] This is a rough estimate of drive (as opposed to heat) requirements.

[2] All these applications are assumed to be obligatorily electrical even though some are likely in practice to be readily substitutable—e.g., by compressed air.

[3] For the temperature distribution of process heat, see appendix II.

[4] The 0.33 quads of fossil fuel used to generate electricity at industrial sites is abritrarily assumed to provide its output to "other electrical"; the exact mix is unknown.

[5] The total delivered enthalpy shown in table 1 is: 49.64 plus 6.69 equals 56.33 quads.

Note: For comparison, the approximate distribution of Canadian end-use energy by thermodynamic eategory is (see Figure 1); 42 percent heat below 100°C, 20 percent heat 100°C. to 260°C, 5 to 7 percent heat above 260 C, 25 percent portable liquids. 1 percent feedstocks, and about 5 to 7 percent obligatorily electrical. This is strikingly similar to the U.S. distribution, with slightly more low-grade heat and slightly less vehicle fuel.

Source: From table 1 and appendix II.

There is room for infinite argument about the significance of the losses at power stations shown in Table 2, which I have included for clarity and completeness. But however one takes account of the low entropy attained by partitioning entropy (and losing enthalpy) at power stations, it is clear that the specialized applications that can take greatest advantage of electricity's high quality are but a small fraction of all end uses. The reasons for restricting electricity as nearly as possible to those few advantageous end uses—cost, First and Second Law efficiency, elegance, and sociopolitics—will be treated below. Meanwhile, we need merely note that approaching the energy problem from the viewpoint of end-use structure, rather than of the forms of energy most readily made from the most abundant domestic fuels, gives a very different impression of what kinds of energy we need.[9]

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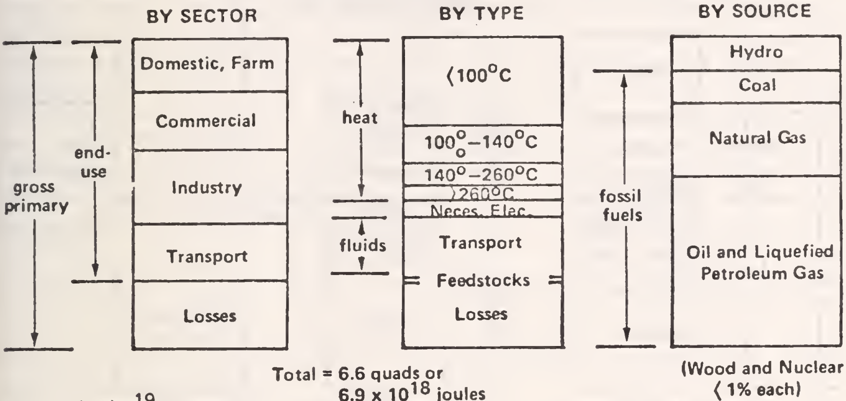
[9] Similar methodological lesson—lung demand-oriented, matching quality to end-use needs, etc.—are just starting to be learned in other resource problems such as water. A systematic survey of what we have learned the hard way in energy policy should be useful elsewhere.

To fix ideas, let us consider the approximate end-use structure of a structurally similar country, Canada. As in the United States, end use is mostly heat, most of that at modest temperatures, and nearly all the rest liquids for transport (Figure 1). The end uses requiring electricity for purposes other than making small temperature differences are so few that all of them, plus all high-temperature heat needs, could be covered (on an aggregated basis, but a fairly realistic one) by present Canadian Hydroelectric capacity. It is thus not obvious that additional electricity can be used to advantage: the same situation I have found in each of about 14 other countries in the past year.



Total = 6.6 quads or 6.9 x 10^{18} joules

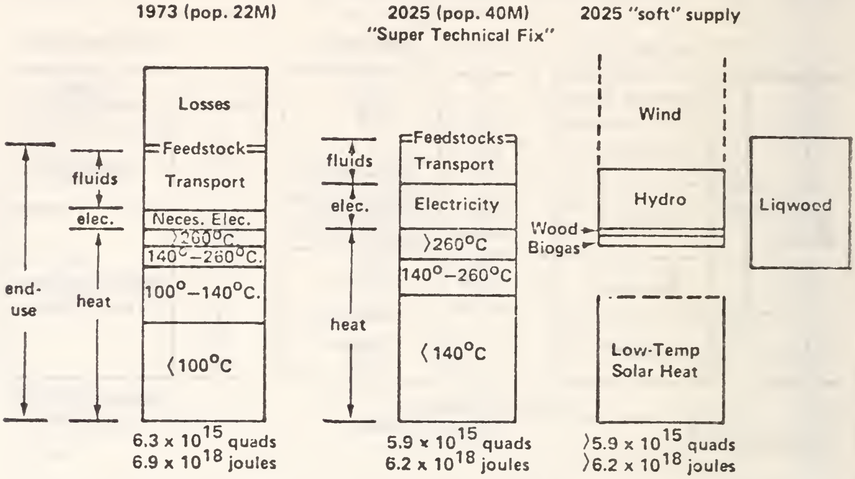
(Wood and Nuclear < 1% each)

Source: Lovins[19]

FIGURE 1.—CANADIAN ENERGY USE, 1973 (POPULATION 22 MILLION)

A study [19] sponsored by the Science Council of Canada takes this logic one step further. The Canadian Cabinet has approved in principle, and the Government is now implementing, technical fixes that are officially estimated to hold roughly constant, over the next 15 years, the primary energy needed to heat houses and to run the transport and commercial sectors, despite normally continuing secular growth. But whereas official calculations run only to 1990, capital stocks turn over so slowly that only half the housing stock, for example, is expected to be replaced by 2025. The technical fixes thus have large long-term effects that are invisible in short-term calculations. My estimates, considered by Canadian officials to be technically conservative, suggest [19] that technical fixes similar to those already approved in Canada, combined with a standard growth projection (with modest exceptions), will yield in 50 years a halving of today's per capita primary energy. (Applying essentially the same technical fixes to the per capita activity levels of 1960—perhaps a rough surrogate for a luxurious version of a "Conserver Society"—would yield a further halving—i.e., to a per capita level roughly one-fourth today's U.S. level, or about that of New Zealand.)

The middle bar in Figure 2 shows the approximate estimated end-use structure for the higher of these two estimates, allowing for population growth to 1.74 times the 1976 level and probably exaggerating the needs for high-quality energy. The figure also includes some elements of supply, to show graphically in a back-of-the-envelope fashion how the concept of end-use matching [1] can be applied. The hydro block is the grandiose and controversial minimum hydroelectric capacity already firmly committed for 1985 (not counting the James Bay project, whose future is uncertain), and substantially exceeds the electrical requirements in 2025 for all purposes other than low-grade heating and cooling. Figure 2 assumes that 50 years is long enough to supply essentially all space heating, plus perhaps some medium-temperature process heat, with solar collection incorporating seasonal storage. (This is technically and economically feasible under Canadian conditions, [19] and the main uncertainty is in the deployment rate; people who think it will take longer than 50 years are welcome to change 2025 to a later date and stretch out the transition.) The box labeled "liqwood" is the Canadian Forestry Service's name and estimate (2.55 quads/year) for the conservatively sustainable net yield of fuel alcohols from forestry if pulp and paper production is held at the present level. The estimate may prove too high on further ecological study, but is far larger than is needed to run the transport sector, even today. Finally, wind is an unknown but very large number (far off-scale): for example, if instead of flooding the Phase One (LaGrande Complex) watershed of James Bay we built currently commercial Canadian wind machines there, we would obtain about 13,000 MW average output instead of 8,300 MW at broadly comparable unit cost, from an area that is not particularly windy.[19] Further, wind can make electricity (or hydrogen) if desired, but can also pump heat, compress air, and otherwise fit anywhere into the end-use structure.


1973 (pop. 22M)
2025 (pop. 40M)
"Super Technical Fix"
2025 "soft" supply
Losses
Feedstock
Transport
Neces. Elec.
›260°C.
140°–260°C.
100°–140°C.
‹100°C
end-use
fluids
elec.
heat
6.3 x 10^15 quads
6.9 x 10^18 joules
Feedstocks
Transport
Electricity
›260°C
140°–260°C
‹140°C
fluids
elec.
heat
5.9 x 10^15 quads
6.2 x 10^18 joules
Wind
Hydro
Wood
Biogas
Low-Temp Solar Heat
›5.9 x 10^15 quads
›6.2 x 10^18 joules
Liqwood

Source Lovins[19]

Figure 2.—Projections of Canadian Energy Use

Inspection suggests that the hydroelectricity already committed, plus any two of the three "soft" sectors, should suffice to match the calculated 2025 end-use structure *in both quantity and type.* In practice, one would instead use a mix of sources. The next steps in this exercise—not yet done for Canada—will be to disaggregate by regions and work backwards [1] through the fossil-fueled transitional period, then to compare the total costs, risks, impacts, etc., of the policy with those of present policy. For two reasons, I expect the results will be attractive. First, pairing off each soft technology with the hard technology that one would otherwise have to use in the long run to do the same thing reveals, as I shall outline below, that the soft technologies are cheaper; the same is probably true for transitional technologies, for similar reasons; so they should all still be cheaper when added up. Second, this exercise has been done for several countries less well placed than Canada, such as Denmark [3, 10] and Japan [3]. In each case, the soft path appears to be quicker and cheaper than present policy, with no worse dependence on imported fossil fuels during the execution of the soft path than without it. (This is because end-use efficiency and soft technologies can each grow faster than hard technologies.)

The traditional objection to such a soft path is that its supply technologies would be far more costly than conventional hard technologies. Let us now examine this thesis.

COSTS

Before we plunge into the numbers, a few caveats are in order. First, the cost calculations below are approximate, illustrative, incomplete, even naive. Their style will be more familiar to a physicist than to an economist. Though I consider the calculations adequate to support the tentative conclusions drawn, they need refinement, which I earnestly hope readers will attempt.

Second, I shall concentrate not on life-cycle costs but on initial costs, for the following reasons:

(1) Though most thoughtful analysts agree that most or all of our fossil fuels are currently too cheap relative to the real costs of depleting them (future depletion is heavily discounted), trying to estimate what fuels should or will cost decades from now is entirely guesswork, since long-term market-clearing prices depend heavily on future taxes, subsidies, negotiable economic rents, etc., not on ideal free-market equilibria.

(2) Since any soft technology, given ordinarily good engineering, will have an operation and maintenance cost lower than the *sum* of fuel cost and operation and maintenance cost for a conventional technology (which, unlike the soft one, requires fuel), the soft technology will have a lower life-cycle cost than the hard technology if the soft one has a lower (or even a slightly higher [10]) capital cost.

(3) Since virtually all significant energy technologies at the margin are capital intensive, their capital cost is an increasingly dominant term in life-cycle cost, and, to first order, provides the long-term signals that one would otherwise seek from life-cycle cost.

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[10] At a 10-percent/year discount rate the present value of 40 years of fuel costs for a reactor ordered today is approximately 42 percent of its initial capital cost, assuming no further rise in fuel costs.

(4) Capital cost is an engineering number that can be calculated, even for future production, with far more confidence than future fuel costs, for it is relatively resistant to the interfering effects of tax, price regulation, and oligopoly.

(5) The drastic capital-cost escalation that has befallen some adventurous hard technologies in the past few years is unlikely to afflict soft technologies to any remotely similar degree, since they are technically more mature, [14] far simpler, and more acceptable to the public.

(6) Engineering calculations provide information that is unobtainable in principle from any kind of economic analysis (e.g., no amount of regressions of historical elasticities can tell you that you can build a heat pump).

A third caveat, as argued elsewhere [1], is that it is essential to compare the costs of alternative *complete* energy systems needed *in the long run* to perform a given *end-use* task. Otherwise one cannot avoid long-term misallocations of resources. Marginal-cost pricing of fuels is not enough, as one must compare the costs of different ways of performing a *function*, not just of delivering a fuel. (Thus capital cost per delivered daily barrel of enthalpy, for example, must be complemented by consideration of how efficiently that delivered enthalpy, of whatever quality it may be, will be translated into end-use function: an example is considered later for space heating.) Though a few analysts are starting to look at whole-system costs of performing a function, no institution today does so. Vertically integrated major oil companies, uniquely, perceive whole-system costs because they own all the pieces, but they only see costs per daily barrel or per barrel of output, not per unit of function. Likewise, utilities are not concerned with end-use function, but only seek the cheapest source of large blocks of busbar electricity to feed into the grid.

Fourth, a serious question can be raised whether economic calculations are particularly relevant today. Of course, sophisticated managers realize that they should base investment decisions on sensitivity to altered circumstances rather than on tiny marginal-cost differences in the base case. But are even enormous marginal-cost differences that important? Is cheap energy necessary—or even desirable? (Paul Ehrlich argues [20] that plentiful cheap energy can be considered less a benefit then a *cost* because of the very expensive damage it lets us do—or its conversion unavoidably does—to essential life-support systems.) As Alan Poole cogently argues. [21]

> The ultimate condemnation of a project is that it is "uneconomic," which is to say it costs 5 mills per kWh more than another option. By comparison, human labor in a dirt-poor preindustrial society costs roughly 2,000 mills/0.5 kWh, 4,000 mills per kWh. In this light I find it odd that so little work has been done on the long-term importance of the cost of energy. Does it really matter if, say, a solar option costs twice as much as a nuclear option? In the conventional wisdom such a price discrepancy would dismiss the solar option automatically even if we were rather concerned about the long-term implications of nuclear power. A pretty good hand-waving case can be made that the effect on economic growth is not very important. A number of European countries appear to have had real energy costs substantially higher than ours yet their per capita GNP is comparable.

Moreover, as Kneese points out, [22] the usual cost-benefit or cost-cost comparisons break down when some costs are not quantifiable (and may hence seem less real than benefits) or are transferred to other times and places (which makes the theoretical basis of cost-benefit comparison invalid). In my opinion, the noneconomic aspects of, say, nuclear power are vastly more important, both theoretically and politically, than its disputed and probably unknowable economic properties. Even Keynes admonished us not to "overstate the importance of the economic problem, or sacrifice to its supposed necessities other matters of greater and more permanent significance." [23]

With these substantial caveats in mind, let us now try to compute a few capital costs, first for central electric systems and then for others, both hard and soft. I shall use the data base of the Bechtel Energy Supply Planning Model, [24] expressed in third-quarter 1974 dollars for ordering early in 1974. The data base, like any, could be improved, but is probably the most detailed, authoritative, and up to date available, and is used extensively in Federal and private studies today. It is being continuously updated.

The Bechtel estimate of direct construction cost—architect-engineer's passthrough—for a 1.1-gigawatt (GW) light-water reactor is $418/kW installed.[11] To this must be added 40 percent for indirect or owner's cost—interest during construction, design, and administration—for a total of $585/kW installed. This is comparable to the $520/kW (also 1974 dollars) assumed by the Brookhaven data base, [25] which relies on the out-of-date (July 1973) and poorly documented A. D. Little study for Northeast Utilities.

Associated with a marginal GW of generating capacity in a typical U.S. program is about 140 miles of transmission circuit [26] with updated nominal characteristics, shown in Table 3. From these data, total capital cost of transmission (direct plus owner's costs, 1974 dollars) per marginal kilowatt of generation is about $69/kW. (The corresponding 1973 and 1985 average costs are about $87/kW and $80/kW, respectively, internally consistent within rounding errors.) The Brookhaven estimate of $75/kW (1974 dollars) is fairly close. Note, however, that the current-dollar escalation rate averaged about 11 percent/year during 1966–1972, when GNP inflation was relatively slow and steady, and that regional cost variations are about 3.5-fold. [27] I shall take as authoritative the Bechtel data, [26] which are based on extensive field experience and checked with utility and Federal Power Commission data.

The Bechtel estimate [24, 26] of capital cost for distribution assumes a nominal 160-MVA-input facility that feeds 29 MW, 21 MW, and 70.2 MW to industrial 34.5 kV, commercial 13.2-kV, and domestic 220-V customers, respectively, at an average power factor such that MVA×0.823=MW. Direct construction cost (1974 dollars) [26] is $34.5 million with all lines aerial, $55 million with all lines underground, and $41 million, or $256,000/MVA, for a nominal split (about 80 percent underground) considered realistic at the margin. Indirect costs [24] are 35 percent. Total distribution capital cost is thus about $420/kW (1974 dollars). Since the Brookhaven estimate is only $145/kW, I have queried the Bechtel estimate with special care and am assured that internal review has confirmed it as realistic.[12] Bechtel believes [26] that lower utility estimates reflect less stringent undergrounding assumptions and special internal accounting procedures that reduce apparent overheads and cost of money.

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[11] Many current data—e.g., the Rancho Seco 2 projections [28]—strongly suggest that this figure is already 10 to 25 percent too low.

[12] The original error-band estimate [24] is −10 percent, +20 percent, with an exponential scaling factor 0.7.

TABLE 3.—NOMINAL CHARACTERISTICS FOR TRANSMISSION CIRCUITS

kV	MVA/facility		GW-miles per facility[2]	Million dollars per facility[3]	Approximate modal split[1]		
	In	Out			1973	1985	Marginal 1973–85[4]
230	600	530	125	95	0.47	0.32	0.185
345	1,200	1,060	300	120	.23	.27	.30
500	2,600	2,450	600	188	.23	.29	.335
765	4,000	3,800	1,250	228	.05	.09	.12
400DC	1,400	1,370	1,200	317	.02	.04	.055

[1] Fraction of total energy transmitted per mode (not fraction of facilities per mode).
[2] GW transmitted; to express in terms of GW generating capacity, divide by 0.791.
[3] Direct construction cost, 3d-quarter 1974 dollars; for owner's costs add 20 percent.
[4] My computation; generating capacity 415 GW in 1973 and 899 GW [24] in 1985.

Source: Carasso and Gallagher. [19]

The Bechtel estimates [24] also used by Brookhaven, for marginal capital costs of nuclear fuel-cycle facilities yield a total cost of about $61/kW installed. I believe this figure is too low by a substantial factor [28] (probably at least two), in view of recent escalation and altered regulatory requirements. Nevertheless, I shall use it.

A fairly up-to-date estimate of the approximate capital cost of the initial core—a front-end cost even though it can be credited later against fuel-cycle costs—is shown in Table 4 in 1976 dollars for 1976 ordering. [28] I shall thus take the initial core cost as $100/kW installed (1976 dollars). Total cost per *installed* kilowatt is thus $585+69+420+61=$1,135 in 1974 dollars plus $100 in 1976 dollars. The empirical capacity factor of the system to mid-1976 is about 0.58. Some analysts argue that this will improve on a "learning curve"; others question whether this theory is applicable in the circumstances peculiar to nuclear engineering with possibly declining quality control, and note that the infirmities of light water reactors (LWR's) appear from outage analysis to be proceeding from the pediatric to the geriatric with scarcely a pause. In any event, since the lifetime average capacity factor assumed in the Atomic Energy Commission Document WASH-1139(74), page 23 is 0.57, since performance appears to be deteriorating with increasing unit size, and since international experience is ambiguous (West Germany vs. Japan), I shall use a generally acceptable 0.55 for lack of a better value. Moreover, since I have not been able to find definitive data or whether the corresponding capacity factor for marginal transmission and distribution equipment should be higher or lower than for the power station, I shall use 0.55 for all the components. The total cost per kilowatt *sent out* is thus $2,064 in 1974 dollars plus $182 in 1976 dollars. Adding a surcharge of 12 percent for transmission and distribution losses (the Bechtel data [24] show average losses of 8.4 percent and 8.7 percent, respectively) yields a total cost per kilowatt *delivered* of $2,311 in 1974 dollars plus $200 in 1976 dollars.

TABLE 4.—CAPITAL COST OF INITIAL CORE OF 1-GW PRESSURIZED WATER REACTOR [1]

	Millions of dollars
Direct cost:	
400,023 lb U_3C_8 at $42/lb	$16.8×3=$50.4
153,838 kg U to convert at $3.50/kg	.5×3= 1.6
135,068 kg U to enrich at $67.25/kgSW, 27,001 kg U at 2.63 percent (74,685 SWU)	5.0×3= 15.1
28,994 kg U to fabricate at $90/kg	2.6×3= 7.8
	74.9/GW
Interest compounded at 12 percent per year with 3-year lead time for U_3O_8 production and conversion, 1.5 years for enrichment, 0.6 years for fabrication	24.4/GW
Total cost (excluding insurance, property taxes, other minor overheads)	99.3/GW

[1] Initial design enrichment 2.63 percent, tails assay 0.3 percent, once-through fuel cycle, values for annual core (including standard process losses).

Source: Harding [28].

We now have the difficult task of putting everything in 1976 dollars for 1976 ordering. One crude approximation, certainly too low, would be to inflate all the items in 1974 dollars by a standard index for general construction, such as Handy-Whitman. This might yield a total of about $3,068/kW delivered. A better approximation would be inflate the nuclear plant component at the observed rate carefully derived by Bupp et al.[29][13]—on the order of 15 percent/year in current or 7 percent/year in constant dollars—yielding $1,575 for the station, $200 for the initial core, and (assuming, somewhat arbitrarily, a 1974–1976 inflator of about 25 percent based on the Marshall & Stevens Equipment Cost Index[25]) $1,245 for total transmission and distribution and $155/kW for fuel-cycle facilities. On this basis, the grand total in 1976 dollars, ordering in 1976, would be $3,179/kW delivered, or about $213,000/daily barrel delivered.

Of course, all these data can be greatly refined and improved—though it may not be worth working hard on second and third significant figures in view of the major unknowns in future escalation rates. The main defect in the approach illustrated seems to me rather to be that one should take account both of generating mix (for different parts of the load-duration curve) and of user diversity. On the former point, clearly gas turbines, combined-cycle plants, etc., are less capital-intensive than baseload stations. Since transmission and distribution (especially the latter, which siting near load centers would not greatly reduce) cost about as much as a nuclear station, however, the sensitivity of total investment to plant mix is reduced. Moreover, detailed data on capital costs of complete electrical networks, including a realistic generating mix, appear not to be available. The only recent number I can find is an estimate[30] of $2,000 capital cost per average kW of capacity to deliver to consolidated Edison customers in New York City (where land and underground cable costs are high). This number appears to refer to capital cost per kilowatt installed, not sent out or delivered, and should presumably therefore be roughly doubled to reflect cost per kilowatt delivered. Moreover, most long-term projections of generation mix assume that nuclear capacity will extend far beyond the present baseload level and that much of the current intermediate-load and gas-turbine territory will be occupied by very capital-intensive pumped storage schemes.[31]

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[13] The undocumented escalation rates used in The Atomic Energy Commission publication WASH-1345 (1974) are virtually useless. More recent work by Bupp shows better correlation coefficients for regressions with LWR costs escalation at 20 percent/year in constant dollars (26 in current dollars), which would yield a whole-system cost of $3,496 per kilowatt delivered, not the $3,179 shown here.

As for user diversity—the fact that not all users will demand electricity at once, so they can share capacity—it is a real issue on which better data are needed. It is not particularly relevant, though, to the specific application I shall examine below, space heating, since European experience clearly shows that the winter peak heating load determines the system's simultaneous maximum demand with negligible user diversity. For industrial process heat (which, from resistance heaters, accounts for 60 percent of the marginal electricity use in the Energy Research and Development Administration's (ERDA) 1975 "intensive electrification" scenario, [32] or more electricity than the U.S. used for everything in 1975) one can again probably assume a good approximation to base-loading, so the question does not arise. For intermittent applications such as home appliances it clearly does arise and should be taken into account—though the, terms to which a large correction factor would apply seem small.

It is also important to note what the above estimate of over $200,000/daily barrel does not include: marginal capital investment in land, reserve margin and spinning reserve, [31] taxpayer-supported regulation and security services, Federal R&D, future services (waste management and decommissioning), and end-use devices. No allowance is made for escalation after 1976 beyond the GNP inflation rate—presumably a highly conservative assumption—nor for the energy that must be debited against station output to operate the nuclear fuel cycle (a debit of about 6 to 8.5 percent for most LWR's). [34] A realistic calculation including all these terms except end-use devices, and still excluding all externalities and dynamic net-energy considerations, [3] would yield a nuclear capital cost nearer $300,000/daily barrel, or close to $5,000/kW delivered. The numbers at this point obviously become fuzzy because proper data are not available and, for some terms, may never become available. Nonetheless the estimate of over $3,000/kW seems unrealistically low.

For comparison with this figure, the Bechtel data [24] for 800-MW coal-electric plants, averaging over the various types of coal and of coal mines and delivery systems in a typical U.S. program, [24] are about $355/kW installed (1974 dollars, direct plus owner's costs). About $106/kW for the fuel cycle and $120/kW for scrubbers must be added. [24] Assuming 1974–1976 inflation for the plant [29] and scrubbers of about 13 percent/year in current dollars, a 1974–1976 inflator of about 25 percent as assumed above for transmission and distribution (T&D) equipment and of 20 percent for the fuel cycle, a 12 percent surcharge for T&D losses as above, and a predicted effective capacity factor of 62 percent [33] for all components yields a total system cost of $2,476/kW delivered, or about $166,000/daily barrel delivered enthalpy. The omitted terms are analogous to, but presumably smaller than, those for nuclear power as summarized above.

Neither of these calculations is, strictly speaking, a whole-system cost, not only because of their noted omissions, but also because neither calculates the cost of supplying a unit of end-use function and thus takes proper account of the low entropy of the form of energy being supplied. An example is worked out below.

The inherent capital intensity of the complex devices needed to make large blocks of electricity is impressive. I am even more impressed, however, by the little-known diseconomy of distributing centrally generated electricity in a country whose load density averaged over 1965–1971, ranged from about 0.61 to 230 mW/square meter (m^2) (mean about 30 mW/m^2) [27] and whose time-averaged load density for residential and small light and power consumers ranged from about 1.2 to 500 mW/m^2 (mean about 15 mW/m^2)[14]. (Both sets of data refer *only* to investor-owned lower-48 U.S. utilities, which had about 80 percent of the total U.S. utility business with about 258,000 large customers and 54.2 million small ones—whereas all utilities combined had about 363 million of the latter.) A recent study [27] finds:

> Transmission and distribution costs contribute significantly to the total costs of providing electrical service. In 1974, privately-owned electric utilities in the United States spent about 35 percent (over $7 billion) of their total capital expenditures for transmission and distribution equipment. The expenditures for operation and maintenance of this equipment were about $3.0 billion, an amount equal to about one-half the total costs of fuel in 1972.
>
> The costs derived from the transmission and distribution (T&D) system have historically comprised about two-thirds the costs of producing and delivering electricity to residential-commercial customers, and over one-third the total costs [of] supplying electricity to large industrial customers.

The study concentrates on major terms—high-voltage transmission lines, distribution lines, and operation and maintenance costs of the T&D system. These three terms together account for about 80 percent of total T&D costs. When capital costs are converted into million dollars/kWh charges at a 13.5 percent annual fixed charge rate, the remarkable results of Table 5 emerge.

The authors conclude: [27]

> . . . almost 70 percent [69.3 percent] of the costs of power to residential and small light and power customers are related to transmission and distribution. Of this 70 percent, almost half [49.3 percent of the total T&D costs] can be attributed to costs of installing transmission and distribution lines, the two items of T&D equipment that exhibited the most significant regional cost variations. For large light and power customers on the other hand, transmission equipment related costs are only 34 percent of the total cost of power, while generation comprises about 55 percent. Distribution equipment and operation and maintenance, including billing, comprise the other 11 percent.

TABLE 5.—NATIONAL AVERAGE COSTS OF U.S. PRIVATELY OWNED UTILITIES, 1972

Item	Cents per kilowatt-hours sold Residential and commercial	Industrial
Transmission equipment	0.45	0.43
Distribution equipment	.58	.06
Operation and maintenance of T. & D	.50	.08
Total T. & D	1.54	.57
Estimated cost of generation	.69	.69
Estimated total cost (delivered)	2.23	1.26
Average revenue	2.37	1.17

Source: Boughman and Bottaro.[27]

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[14] Implying that an average 1-GW plant serves a radius of 146 kilometer (km); the actual average haul length is of the order of 343 GW-km/GW.

To put it differently, for the smaller customers (average load 1.04 kW) who accounted for about 55 percent of the annual energy sales in the whole sample, a dollar spent on electricity was allocated approximately 19 percent to transmission equipment, 24 percent to distribution equipment, 21 percent to operation and maintenance of all that equipment (including metering—a small term—and billing) about 6 percent to profit and to arithmetic discrepancies in the analysis (owing largely to differential escalation of various components)—and *only 29 percent to electricity.* This seems to me an undeniable diseconomy of centralization. I am sure utility customers would be surprised to learn that they are paying 2.2 times as much to have the electricity delivered to them as to generate it. For the large customers (average load 177 kW), the mix is less extreme—generation cost is 1.2 times delivery cost—but still odd, and suggests that there are strong economic incentives for central electrification to encourage centralized use patterns. The wide regional variation in these values—the 1972 T&D cost ranged from 1.0 to 2.3 cents/kWh for small and from 0.36 to 0.82 cents/kWh for large customers—does not alter the startling size of the T&D overheads.[15] It does not appear from the data presented [27] that truly marginal (rather than recent historic) costs would tell a very different story. It would be interesting to check that, though, and to see whether public utilities (about a quarter the total size of the private ones surveyed) yield similar results.

Direct fossil-fuel systems are surveyed in detail by Bechtel [24] with the results (used also in the Brookhaven model [25] shown in Table 6. The costs are approximate total marginal capital costs (direct plus owner's costs) in 1974 dollars per daily barrel, ordering in early 1974. Since the delivery-system costs are a function of the source, the detailed structure of the distribution system should be calculated separately in each case. In general, the Arctic sources, with low wellhead investment, entail high transport investment (an Arctic gas pipeline ordered now could easily cost much more [35] than the wellhead investment). The exact data (insofar as anyone knows them) are in principle available from the Bechtel data base, [24] but would require very laborious calculations of modal splits. As a crude approximation, therefore, one can only combine weighted averages of sources in each category with weighted average costs of delivery. The result in 1976, dollars, ordering in 1976, is approximately $2,800 for domestic coal, $7,200 for the oil sources shown, and $13,100 for the gas sources shown. Both the latter figures are significantly lowered by the inclusion of imports (imported oil is only about as capital-intensive as domestic coal, a few thousand dollars/daily barrel). It appears that domestic frontier fluids fall generally in the range $10,000 to $25,000/daily barrel in 1976 dollars.

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[15] Since 1 barrel=5.8 gigajoule and 1 kWh=3.6 megajoule, 1 cent/kWh=$16.1/barrel enthalpic equivalent;

TABLE 6.—TOTAL MARGINAL CAPITAL COSTS FOR DIRECT FOSSIL FUEL SYSTEMS

	(1974 dollars/daily barrel))	
System	Exploration/development/production cost at well-head/mine-mouth/terminal	Cost of system to process/deliver to consumer [1]
Domestic coal: weighted average	[1] $1,437	
Eastern underground	1,150	
Eastern surface	1,980	$1,380
Western underground	968	
Western surface	1,150	
Crude oil import	110	
Alaskan oil	803	3,697
Offshore lower-48 oil	11,594	
Oil shale	9,823	
Liquefied natural gas import	1,034	
Alaskan gas	3,410	4,698
Offshore lower-48 gas	11,594	
Onshore lower-48 gas	12,496	

[1] Average weighted by the modal mix (for both sources and means of transport) calculated by the Bechtel model [24] as optimal for President Ford's January 1975 energy program for 1976–85.

As for coal synthetics, the Bechtel data [24] relied on by the Brookhaven model [25] are in the range (1974 dollars and ordering) from $14,900/daily barrel for low-BTU gas to $20,700 for pipeline-quality gas and $34,300 for methanol. (Brookhaven estimates [25] $12,500 for hydrogen.) These estimates do not include, however, the fuel cycle, water supply, or delivery system (though the latter might rely on pipe already laid). Broadly comparable estimates are given in the November 1975 Interagency Task Force report on synthetic fuels. September 1975 data [35] suggest that the specific investment (1975 dollars) in a Lurgi plant is of the order of $18,000/daily barrel for Western and $20,000 for Eastern coals, with about a 20 percent saving possible with second-generation (e.g., HYGAS) technology. The total cost for such an advanced plant, including the fuel cycle, water supply, and connections to existing pipelines, would be of the order of $22,000/daily barrel "or more," [35] roughly comparable to the cost of a tar-sands system. The extraordinary escalation of most synthetic-fuels projects in the past 2 years, however, makes me suspect, with Arthur Squires, that a whole-system capital cost around $40,000/daily barrel in 1976 dollars, ordering now and excluding pipelines, is probably realistic, and might even be low if such rapid escalation continued for long.

Let us turn now to transitional fossil-fuel technologies. [1] Though no detailed cost estimates appear to be available for small-scale coal conventional large-scale conversion—by e.g., the flash processes [36] or supercritical gas extraction [37]—both seem technically simpler and more reliable than conventional large-scale conversion, and it would be suprising if they did not have correspondingly lower capital costs and escalation rates. Firmer estimates can be given for the fluidized-bed technologies—for industrial and institutional boiler backfits, cogeneration,[16] and district heating—on which I believe strong and immediate commercial emphasis is warranted. [1, 38] I have unfortunately been unable to find out the tender prices for the 25-MW(t) thermal Enköpings Värmeverk fluidized-bed boiler now under construction by a Norwegian-Finnish consortium that is operating a 2-MW version commercially. (I wrongly cited 25-MW/Enköping as 15-MW/Linköping.) A detailed design study by Stal-Laval Turbin AB (Finspong, Sweden) has been developed, however, to the point of cost estimates on which a commercial tender could be based. [39] After distribution losses, the Stal-Laval system [1] would deliver 60 MW plus 105 MW(t) of district heating. If we assume that the electricity is used in heat pumps with COP=2, total delivered space heat is 225 MW(t). Recent estimates [39] of total construction costs (including interest and standby boilers) are $40 million for the plant and $25 million for the district heating grid, [40] both appear generous.[17] If all electrical distribution were counted as marginal—which it might not be—it would add about $35 million. Heat pumps at a rather generous $200/kW would add $12 million. The grand total implies a system cost of $33,400/daily barrel delivered heat. To this must be added a few thousand dollars for the fuel cycle and some allowance for capacity factor (though the latter modification would presumably be very small, since the capacity factor should be extremely high, and outages would be covered by the standby boilers already allowed for). I suspect that both these terms would be more than covered by conservatisms in the cost estimates, and that a round number in the vicinity of $30,000/daily barrel (1976 dollars) is realistic.

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[16] Robert Williams tells me that the SRI estimate [1] that 29 percent of West German electricity comes from cogeneration is incorrect: apparently some 23 to 25 percent is generated at industrial sites, but only about half is true cogeneration rather than condensing turbines. I regret the error and shall seek to correct it when Foreign Affairs corrects note 25. [10]

It would be particularly interesting to have firmer cost estimates for fluidized-bed industrial boiler backfits—first at atmospheric, but then at elevated pressures suitable for later conversion to gas-turbine cogeneration, via either direct or closed cycles.[42] The sharing of investment between electrical and process-steam functions seems attractive [41] indeed, utility-owned industrial cogeneration by 1985 could be profitably generating 26 to 42 percent more than all U.S. utility sales of electricity in 1975. [41] Better field data for pressurized fluidized beds—generally conceded to be cheaper than those at atmospheric pressure—should become available in the next year. Data for pressurized trash and wood-wasteburners of this type are also relevant, though I have not yet obtained firm cost figures for such designs as Combustion Power Co.'s 11-MW+$61,000 pounds/hour CPU-400 system [reportedly about $15,000/(input ton-day)].

Let us turn now to the capital costs of soft energy technologies,[1] beginning with wind machines. Unfortunately, all available modern data refer only to wind-electric systems, though mechanical work from wind may be used more cost-effectively for pumping heat or water, compressing air, etc.[1] Moreover, the field is developing very rapidly, and details of many of the most interesting studies are not yet published (e.g., Lockheed-California's estimates for ERDA of low mass-production costs for horizontal-axis machines—the sort of technology that mass-production cost specialists can handle with confidence because it rests on mature engineering). Data on some intriguing systems, such as James Yen's Grumman vortex tower, are also not yet firmly developed.

As a baseline, however, we can take a currently commercial 200-kW vertical-axis Darrieus device made by Dominion Aluminum Fabricating Ltd. (Mississauga, Ontario). The first such device is currently being installed by Hydro-Quebec on the Magdalen Islands in the Gulf of St. Lawrence. It has two blades in tensile stress, is 80 feet in diameter, and has a 120-foot shaft atop a 30-foot tower. It is expected to supply about 0.5 GWh to the grid annually at 3.5 to 4.0 cents/kWh from a site with average windspeed of 18 to 19.5 miles/hour. The installed capital cost, turnkey except foundation and grid connection, is $235,000 (1976 Canadian dollars, nearly the same as U.S. dollars). But this cost includes virtually the whole investment in the large extrusion dies. Accordingly, the second unit has a list price of $175,000 FOB factory (exclusive of switchgear), with further marked declines thereafter. The run-on production cost in small lots (tens) is probably $90,000 to $100,000 and the corresponding price about $130,000. Cost estimates for larger orders (or for the 1-MW unit under development) are not yet available. If we take the total installed price for small-lots production as $150,000 (1976 dollars) and assume a capacity factor of about 0.3, characteristic of respectable sites, the capital cost is $2,500 per average kilowatt sent out. Since trunk transmission would be avoided by feeding directly into local lines, distribution loss of about 4 percent seems reasonable. If we assume that a third of the 600-VAC-and-downwards distribution investment (altogether of the order of $380/kW) is at the margin, the whole-system cost might be about $204,000/daily barrel delivered enthalpy, less than that of an LWR. It could be more reasonable to assume that the entire distribution investment has already been sunk, however, just as one might assume the same for pipelines associated with a new coal-gas plant. This is because the wind system would normally be used as a fuel-saver integrated into the existing fossil-plus-hydro grid. Such supplementary use makes more sense than a attempt to imitate, with full storage, the operation of existing central stations. Of course, it might make even more sense to use the mechanical work directly to pump heat or compress air at the point of end use, and in such a system the storage required would be simple and cheap.[1]

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[17] For example, the Thermo-Electron study [41] estimates that a new conventional industrial gas turbine in this size costs about $170/kW installed without, or $230/kW with, a waste heat boiler. This implies $11.9 or $16.1 million for a conventional 70-MW gas turbine, leaving a large sum for the fluidized bed, coal-handling systems, cyclones, etc.

I do not propose here to develop cost estimates for geothermal heating (a more attractive system than geothermal-electric), partly because many geothermal systems would not be truly soft [1] and none in principle is indefinitely renewable. It is interesting, however, that technical advances in telethermics now permit very remote siting of wells from heat loads. For example, I understand [43] that an insulated pipe in Italy has continuously shipped hot water since 1969 for over 100 km at an average thermal efficiency of 98.5 percent.

Estimates of the capital cost of bioconversion vary widely. One consistent set of estimates in 1974 dollars suggested values from less than $10,000/daily barrel output to about $20,000 for crop residues, and up to as much as $30,000—often less—for municipal waste pyrolysis [44] (which can offer substantial economic credits for recovered materials and for saved disposal costs). [45] For most agricultural projects, $13,000 to $20,000/daily barrel (1976 dollars), plus a few thousand dollars for local delivery systems, might be typical, including collection investment. [46] On the other hand, the local distribution might use existing equipment.

Solar process heat, [47] though attractive and starting to be widely studied, is not yet in a state where definitive cost estimates are generally accepted for a range of designs. Good numbers are about to emerge from the studies described in Appendix II. High working temperatures can be obtained not only by various forms of concentrators but also by highly selective surfaces, either on flat nonfocusing plates or in cylindrical configurations that concentrate severalfold. For example, thin-film sputtering technology now suffices to produce selectivities (ratio of visible absorptivity to infrared emissivity) of 50 to 60, [48] at pilot-scale costs of a few dollars per square meter. It is readily calculated that such a surface, suitably insulated and contained in a hard vacuum, is so insensitive to cloudiness that it should provide working temperatures, under load, of the order of 400° to 600° C on a cloudy day in the winter at Scandinavian latitudes.

Fundamental to any discussion of solar space heating as a major long-term energy technology is the cost of seasonal storage, [19] which eliminates backup investment (and associated potential for load management problems) and can increase collector capacity factors. With modern tank design—prefabricated tongue-and-groove concrete slabs assembled modularly in a hole in the ground, then sprayed with insulating foam, lined, and backfilled—installed costs of hot water storage are about 60 to 95 cents per cubic foot or about $21 to $34 per cubic meter (1975 dollars). [49] With such a tank, the marginal capital cost of the solar heating system now operating with no backup at Lyngby, Denmark,[50] would have been about $6,000 rather than about $8,000—or even less without the high costs of first-of-a-kind design. I suspect that storage costs will drop further as tanks are integrated into buildings: apparently heat-sink tanks up to nearly 5,000 cubic meters are currently used in Japan, partly as seismic stabilizers. [49]

Estimates of the capital cost of solar space heating depend sensitively on both building and collector design. For new buildings, passive systems with negative, zero, or negligible marginal capital cost should suffice. [51] The following discussion thus refers to retrofits requiring hardware. Further, impressive economies are available in principle from mass production of very simple designs. Suitable concepts include Jerry Plunkett's paper-and-phenolic honeycomb sandwich that unrolls like roofing paper, replaces shingles, and is estimated to have a very long lifetime (many decades) and an installed cost of a few dollars per square foot; the Philips tubular collector designed for cloudy northern European latitudes and expected to enter advanced pilot production next year; [18] grids of flexible plastic tubing laid in poured asphalt on a flat roof; plastic tubes imbedded in a lightweight rollable mat like the "Sunmat" made by Calmac; [52] and the Thomason system. [52] Commercial versions of the last two sell today for about $3 to $5 per square foot installed. Their merit of simplicity merits close attention. [51]

Let us be pessimistic, however, and assume that solar heating is to be done with conventional flat-plate assemblies that are not integrated into the building structure, have high transport and installation costs, and involve the inherent assembly and materials costs of high-quality glazing and sheet-metal work. In late 1974, factory prices for such collectors were $10 to $50/m^2, while various versions assembled and delivered, including moderately selective plates, were \$70 to \$120/m^2 for the collector assembly only. [53] Many solar hardware production experts estimate that an installed square meter of high-quality flat-plate collector plus 1 cubic meter of seasonal water storage; [19] complete with all plumbing, will cost about \$150 (1976 dollars) around 1978–1979 and about \$100 in the mid-1980's (1976 dollars)—the period of interest for comparison with hard technologies ordered today, since the latter have about a 10-year lead time.

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[18] Though the envelopes used in current Philips tests use low-pressure sodium-vapor-lamp technology and are thus somewhat larger and heavier than fluorescent-lamp tubes, the latter, at less than 10 cents each, are perhaps the cheapest manufactured commodity per unit mass, and are extruded at about 30 miles per hour. Owens-Illinois uses a similar approach.

Let us apply this \$100/(m^2 + m^3) figure—consistent with estimates of the Office of Technology Assessment and A. D. Little and with detailed analyses by private mass-production specialists—to Denmark. A Danish south wall receives average total insolation [10] of about 125 W/m^2 and modern (double-glazed, slightly selective) flat plates in Danish conditions can achieve a First Law efficiency of about 0.42. Seasonal fluctuations in Denmark do not appear to require—taking account of storage losses—more than about 0.7 m^3 of storage per square meter of collector in a well-insulated house, thus saving about 8 percent of the estimated system cost. (Actually the storage volume and collector area can be traded off against each other.) Completely solar space heating for a typical Danish house (125 m^2 floor) in the mid-1980's should thus cost on of the order of \$118,000/daily barrel delivered enthalpy—about \$3,500 for an average heat load of 2 kW (good insulation) of \$7,000 for a typical 1974 heat load of 4 kW.

The less favorable regions of the United States receive about 180 W/m^2 on an optimally oriented fixed flat plate (about 270 W/m^2 in southwestern deserts), and seasonal fluctuations require even less storage then in Denmark. Typical mid-1980's specific investment for completely solar space heating should thus be of the order of \$50,000 to \$70,000/daily barrel, assuming total insolation of 180 W/m^2. (Extra installation costs of retrofit should be roughly balanced by savings through the reuse of existing hot-water plumbing or hot-air ductwork, though more detailed study of this point would be useful.) All such figures should be treated with caution, not only because they assume fixed technologies in a rapidly changing field, but also because, as Weingart points out, [53] the installed price even of completely conventional, nonsolar domestic water heating systems varied by a factor of more than two in a recent Southern California survey of similar apartment buildings, due to variations in local costs of labor and materials and in the skill (and avarice) of the contractors. The few integrated solar heating and cooling projects now built or being built on a large scale are probably a poor guide to future costs, For example, the Los Alamos project, [53] which ran a \$150/m^2 collector cost up to a \$690/m^2 installed collector cost, appears to be a typical example, like many ERDA-funded solar demonstration projects, of a highly sophisticated and instrumented, therefore excessively complex and costly, installation.[20] Simpler systems, such as the Oss house [54]

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[19] A 100-m^3 tank cycling over 50° C and discharging over a period of 4 months produces 2 kW. My macroeconomic approach makes it unnecessary to worry about partial solar heating with backup, or combined solar heating and cooling, as tricks to make solar heating economic.

[20] I am concerned that major aerospace and defense corporations are so heavily involved in ERDA's solar program: not because they do not have technical resources that we need, but rather because they may not be able to keep the hardware simple enough and the overheads low enough. (Just responding to a recent ERDA coal Request for Proposal would have cost \$2 million!) I am reminded of the new Boeing-Vertol subway cars for Boston, which reportedly used, in the original design, some 1,300 components per door. This was sweated down, with difficulty, to about 300, and the doors might now work, but clearly the designers have become so sophisticated that they can't design a door any more. Mass production is hardly an answer to this institutional problem. [53]

(where 2/3 solar heating competes even with cheap Groningen gas), may be a better measure of realistic overhead levels.

Subject to the numerous caveats above, the *approximate* marginal capital cost (1976 dollars) of complete systems to deliver a daily barrel of enthalpy (not of end-use function!) to a U.S. consumer in the mid-1980's are summarized in Table 7. [1] I have generally neglected future escalation beyond the GNP inflation rate and considered only those soft technologies that are currently state-of-the-art. Even if one quibbles with details, this table suggests several broad conclusions:

TABLE 7. APPROXIMATE MARGINAL CAPITAL COST FOR DELIVERING 1 DAILY BARREL OF ENTHALPY [ABOUT 67 kW(t)] IN THE U.S.

	1976 dollars
Traditional direct fuel technologies, 1950-70	$2,000-3,000
Imported oil or domestic coal, 1970's	2,000-3,000
Frontier oil and gas, 1980's	[1] 10,000-25,000
Coal synthetics and "exotic" hydrocarbons, 1980's	[1] 20,000-40,000
Central coal-electric with scrubbers, 1980's	[1] 170,000
Light-water reactor, mid-1980's	[1] 200,000-300,000
Fluidized-bed gas turbine/district heating/heat pumps, early 1980's	[2] 30,000
Wind-electric	[1] 200,000
Retrofitted 100 percent solar space heat, mid-1980's	[2] 50,000-70,000
Bioconversion of agricultural/forestry residues, 1980's	13,000-20,000
Pyrolysis of municipal wastes, late 1970's	30,000
Improved end-use efficiency:	
New commercial buildings [55]	[2] 3,000
Common industrial/architectural "leak-plugging"	[2] 0-5,000
Most industrial/architectural heat-recovery systems	[2] 5,000-15,000
Difficult, extremely thorough building retrofits	[2] 25,000

[1] Delivered in the form of electricity.
[2] Including cost of end-use devices to deliver desired function.

(1) Big electrical technologies are pricing themselves out of the capital market. It is no wonder that the internal financing ratio of utilities fell from 0.40 to 0.19 during 1960–1973, [56] nor that institutional investment in utility debt has fallen off sharply in the past year or two. The Invisible Fist strikes again.[21]

(2) Improved end-use efficiency will long remain the most cost-effective investment.

(3) Though all major domestic supply technologies available at the margin (with the exception of direct coal) are relatively capital-intensive, the life-cycle and even the capital costs of soft and transitional technologies, viewed in traditional terms (cost per unit of energy or power), are arguably attractive compared with those of complete hard-technology systems.

(4) To make such comparisons specific, one must examine end-uses one by one.

To take up this last point, consider the task of supplying heat at modest temperatures, shown by Table 2 to be the dominant term (34 percent) in U.S. end use, and typically over half of European end use. Let us suppose that my estimate of $50,000 to $70,000/daily barrel for completely solar space heating of an existing building in the mid-1980's (assumed to be very well insulated; which is worthwhile no matter how it is heated), using relatively costly technologies within the present art, is far too low and that a Danish figure, say of the order of \$100,000/daily barrel, is in fact more appropriate for the United States. Let us also suppose that the long-run alternative is, say, an LWR—powered grid (say, \$213,000/daily barrel), operating a heat pump (say \$200/kW) with COP=2.5. The whole-system marginal capital cost of this alternative is thus

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[21] (As in Adam Smith's "*Invisible Hand.*")

$$\frac{\$213{,}000/\text{daily barrel}}{2.5}+\frac{(\$200/\text{kW})\text{x}(67.\ 1\ \text{kW(t)/daily barrel})}{2.5\ \text{kW(t)/kW}}=90{,}700/\text{daily barrel}$$

suggesting that the solar system will certainly win on life-cycle cost and may even win on initial capital cost. (I think the solar system will also have lower life-cycle cost than an equivalent synthetic-fuel-and-furnace system.)

Numerical quibbles apart, several methodological objections might be raised to this calculation. First, it takes no account of user diversity. Second, it takes no account of the likelihood that part of the winter peak load will in fact be met by lower-capital-cost generation such as gas turbines. Both these points were answered earlier. Third, it does not consider the attractions of, say, an ACES [49] system with the potential for higher effective COP. True; but neither does it come close to a true and full accounting of the nuclear costs, even of the conventional internal costs, nor does it take account of the likelihood that urban and even suburban solar retorfits will in fact be technically simpler than assumed here, or on a neighborhood scale with substantially lower unit costs, or both.

This sort of argument is complex and perhaps can't be resolved. It does, however, leave me with the impression that soft-system economics leave a strong prima facie case for proponents of hard technologies to answer.[22] But there are broader perspectives in which to view this comparison. For example:

(1) First Law efficiency. I do not mean by this the First Law efficiency of a soft technology like a solar heating system; it is not an interesting criterion, not only for the reasons adduced by Shurcliff, [52] but also because what is "lost" (not converted from flux to function) is renewable, not depletable,[23] and is either desirable for albedo compensation of (in other soft systems) usable locally as low-grade heat because of small unit scale. I refer rather to the low net First Law efficiency of the electric grid and its fuel cycle—about 0.25 in Britain, for example. A great deal of high-grade fuel is thus used to produce a small amount of delivered enthalpy. The delivered energy is indeed of low entropy; but to compensate for the low First Law efficiency of the grid one would need the equivalent of a reciprocal COP (say, about 3 to 4) in each electrical application in order not, in a real and irreversible sense, to waste precious fuel compared with the First Law efficiency of using the same fuel directly. Analogously, in what significant applications does *electricity* have a high enough First Law efficiency to compensate for its-order-of-magnitude penalty in capital intensity relative to competing systems?

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[22] To say nothing of the economic comparison between electricity and direct fuel use. For example, if fuel oil in the mid-1980's cost, say, \$30/barrel (1984 dollars), while nuclear electricity cost 5 cents/kWh (1984 dollars) at the busbar and only 8 cents/kWh delivered, then an existing oil furnace of 67 percent First Law efficiency will compete with an existing heat pump with COP$\leq$2.87. With capital costs not treated as sunk, the limiting COP would probably rise. It is no wonder that Table 1 shows no electrical water heating or cooking or space heating, and only partial electrical air conditioning, in the cost-conscious commercial sector, despite electrical rate structures favoring large users.

[23] Thus the definition of "primary energy" must shift for soft technologies to show the output of the device, not the gross input of which only some is converted. This approach is used in Figure 2 of reference 1.

(2) Second Law efficiency. [57] This is a more subtle and useful criterion, and makes the same argument emerge even more strongly. Recall that the Second Law efficiency of a typical U.S. domestic gas furnace system in winter is of the order of 0.05, that of a typical New York City office air conditioning system of the order of 0.02, that of a car of the order of 0.12. [15, 57] Plainly any process that uses a flame temperature of kilodegrees of a nuclear temperature of teradegrees to produce a steam temperature of hectodegrees to drive turbines and make electricity of a very high quality, all to make an end-use temperature change of dekadegrees, is going to have an abysmal Second Law efficiency that heat pumps cannot greatly alter. Worse, it is inelegant—a cardinal sin to a physicist. Natural energy fluxes, on the other hand, are off relatively low thermodynamic potential when used diffusely. The 5,800°K potential of concentrated sunlight, the kilodegree potential of fixed carbon, and the infinite effective temperature of wind-derived mechanical work need only be used for applications requiring them, so preserving high Second Law efficiency through end-use matching.

(3) Sociopolitical implications. This crucial perspective—perhaps the most important—is considered elsewhere [1] and in the concluding section of this paper.

Are there not countervailing arguments? Of course there are, notably the convenience with which a utility can control electricity and a user use it. I do not know how to measure convenience; nor am I persuaded that it is as important a criterion as some have proposed, especially at the margin. I have not found that gas mantle lights are significantly more trouble to use and maintain than electric lights—in some respects they are more pleasant [24]—nor that machinery driven by compressed air is in any sense less desirable than electrical machinery. Convenience, however one defines it, can also be dearly bought, and I think many people are getting to the point where they would rather have the trouble (or creative task) of drawing the curtains at night, putting up storm windows, and even adjusting solar plumbing each season than of paying an exorbitant utility bill and living next to a reactor. Badly designed soft technologies can be time consuming; but irrational utility systems can be at least as time consuming in terms of the amount of alienating work that must be done to earn the money to pay the utility bill. Some people think that all soft technologies must be fiddly and entail onerous personal involvement. But to the extent that this is historically true, it is largely because most existing soft hardware is the work of enthusiastic amateur tinkerers who enjoy understanding their own systems and increasing their independence, rather as some people enjoy camping or messing about in boats. I have never seen a respectable engineering argument why soft technologies cannot be as "hands-off" as the domestic systems that we have—and have to fix—today, or even more so. We do, after all, have some solar heating systems that have operated with zero maintenance for 30 years. Likewise, inherently benign soft energy systems ought not to give rise to the hard-to-manage systemic environmental impacts and public nuisances that inherently dirty decentralized technologies like cars have done. The management and maintenance issues are real, and I must not be understood to say that the bad engineering that has plagued heat pumps, reactors, etc., cannot occur in simpler systems. (Many episodes of corroded solar collectors come to mind.) But I think the impact of soft technologies on personal time and care has been much exaggerated. Generally we would need only to return to the standard of engineering and quality control characteristic of many domestic appliances in the 1930's and 1940's.

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[24] I do not know whether they are more dangerous. Electric wiring is the number two cause (after smoking), of the approximately 12,000 annual U.S. deaths in 3 million fires.

Is this argument about the marginal—not historical—convenience and appropriateness of pervasive electrification academic? I think not. Major policy decisions such as whether to proceed with the liquid metal fast breeder reactor program are proposed today on the basis that, say, U.S. electricity "demand" will increase 15-fold, or at least a "conservative" 7.5-fold, by 2020—for what purposes is not made clear. On current ERDA projections, late-1975 U.S. nuclear capacity is to increase 11- to 20-fold by 2000. A cogent new paper, [32] however, argues that on the contrary, no conventional economic or engineering grounds could conceivably justify a nuclear capacity increase above, say, about 6-fold (250 GW) by 2000, and that ERDA projections showing the contrary are spherically senseless. Indeed, it appears [32] that cogeneration in 2000 could provide electricity conservatively equivalent to over two-thirds of the total 1975 electrical demand, directly displacing over 200 GW of projected nuclear capacity.

If existing centralized systems do not now make economic and engineering sense, why were they built? There are at least four rational explanations. First, because objective conditions have changed drastically, [58] and an industry not noted for quick and imaginative responses has been slow to adapt. Second, because centralized energy systems have been built by institutions in no position to ask whether those systems are the best way to perform particular end-use functions—an omission reinforced by our failure to price fuels at long-run marginal cost. Third, at times we have seen powerful institutions deliberately seeking to reinforce their power by constricting consumer choice, as in the classic monopoly tactics of the early electric utilities [59] or the fight against public power and (abroad) private wind machines. Fourth, the long economic shadow cast by large sunk costs has often led us to seek to reinforce past mistakes through subsidies, bailouts, $100-billion slush funds, etc., thus further restricting consumer choice, [60] rather than writing off (or gradually retiring through attrition) ill-conceived infrastructure. Energy decisions are always implemented gradually and incrementally; major shifts take decades. A chief element of strategy, inherent in the soft path, [1] is thus to avoid incremental commitments of resources to major infrastructure that locks us into particular supply patterns for more decades thereafter. We are already stuck with gigantic infrastructure that constrains our choices, and nobody is suggesting we wipe the slate clean. The question is rather what we do at the margin. What made sense when real costs of electricity (both average and marginal) were steadily falling, [58] may need to be reversed when real costs are rapidly rising with no end in sight.

To avoid misinterpretation of my views on electrification, I must make it clear that I am almost—not quite—as unimpressed by the virtues of central-station solar electricity as of central-station fossil or nuclear electricity. Both, in my view, are socially (and economically) unattractive. [1] Some analysts believe, probably on good grounds, that we may well have a large solar-thermal-electric scheme operating in the late 1980's at a cost roughly comparable to the cost of nuclear power at that time (or, according to estimates of the International Institute for Applied Systems Analysis, cheaper than oil-electric power in Central Europe). Such systems would have land requirements of the same order as those of equivalent coal-electric, coal-synthetic, or nuclear-electric fuel cycles, [61] but, unlike them, could coexist with some other land-uses and need cause no really serious scars or impacts. [62] What is not clear to me is why one should want such a system—or, for that matter, equivalent central stations based on the cheap photovoltaic cells (with or without optical concentrators) that seem likely to arrive much sooner. The justification for having cheap photovoltaics would be if they can be used in decentralized fashion—e.g., on houses (either using AC inverters or, preferably, adapting end uses to low-voltage DC). In such circumstances, I would welcome their use where it is thermodynamically advantageous—a criterion subject to both physical and economic tests—or, perhaps, even where it isn't, as that is not the only criterion, and we have already noted that economic rationality is too narrow a test. Dispersed cheap photovoltaics—especially if they can be made cheap relative to direct fuels, not just to central-station electricity—would certainly be useful and should be pursued. I still believe, however, that no solar electric technology is necessary to our national energy supply if we take full advantage of the diversity of soft technologies already demonstrated. [1] Interest in solar electricity is unfortunately reinforced by ERDA's arbitrary and inexplicable 1975 decision that only electrified technologies will be considered capable of making a major long-term contribution.[63]

The illogic of the ERDA position is this: If we are running out of oil and gas but do not like coal, it is said, we need nuclear power; but if we are not going to have nuclear power, we need other systems that would do what nuclear stations would have done—namely, deliver gigawatt blocks of electricity. But we should instead be seeking systems that will do what we would have done with the oil and gas if we had had them in the first place. It is the function that interests us, not substituting for reactors. By not structuring the problem in this way, ERDA has so far failed to grasp the immense short- and medium-term opportunities for deploying available technologies for end-use efficiency, cogeneration, fluidized-bed boiler backfits, organic conversion, and extensive solar space heating. The longer this delay, the worse will be our shortages of clean heat and fluid fuels. [1]

SOCIOPOLITICS

Section IX of reference 1—the pivotal section of that paper—argues that a hard path inevitably entails structural changes with high political costs: that it nurtures dirigiste autarchy, by-passes traditional market mechanisms, concentrates political and economic power, centralizes human settlements, persistently distorts political structures and social priorities, encourages bureaucratization [64] and alienation, compromises professional ethics, is probably inimical to greater distributional equity within and among nations, inequitably divorces costs from benefits, enhances, vulnerability and the paramilitarization of civilian life, introduces major economic and social risks, reinforces current trends toward centrifugal politics and the decline of federalism, and encourages—even requires—elitist technocracy whose exercise erodes the legitimacy of democratic government. Several of these points deserve amplification or qualification.

In a soft energy path, the technological measure to be achieved can be readily separated from the policy instrument used to encourage it. The former—cogeneration, bioconversion, insulation—is per se relatively neutral, the latter politically charged. It is the latter only that is likely to irritate us if ill-conceived. But I believe the policy tool can be chosen, according to practical and ideological convenience, from such an enormous armamentarium that the choice can fully respect pluralism and voluntarism.

I do not see how the same pluralism can possibly extend to a hard, coarse-grained energy path. The scale and the technical difficulty of its enterprises are so vast that corresponding concentrations of social resources must be efficiently mobilized without substantive regard to diverse opinions and circumstances. Only large corporations, encouraged by large government agencies, using large sums of private and public money to employ large numbers of workers on large areas of land, can possibly get the job done. It is not a task for householders, small businesses, block associations, or town meetings.

Soft technologies are thus inherently, structurally less coercive and more participatory than hard technologies. In a nuclear society, nobody can opt out of nuclear risk. In an electrified society, everyone's life style is shaped by the economic imperatives of the energy system, and, from the viewpoint of the consumer, diversity becomes a vanishing luxury. Like purchasers of model T Fords, the consumer can have anything he wants so long as it's electrified. But in a soft path, each person can choose his own risk-benefit balance and his own energy systems to match his own of caution and involvement. People who do not care to partake of the advantages of district heating will be free to reject them—and, if the system is thoughtfully designed, to change their minds later. People who want to drive big cars or inhabit uninsulated houses will be free to do so—and to pay the social costs. People can choose to live in city centers, remote countryside, or in between, without being told their life style is uneconomic. People can choose to minimize what Robert Socolow calls their "consumer humiliation"—their forced dependence on systems they cannot understand, control, diagnose, repair, or modify—or can continue to depend on traditional utilities, for large grids are already with us and in some degree will persist for a long time. In a soft path, then, dissent and diversity are not just a futile gesture but a basis for political action and a spur to private enterprise. But the monolithic nature, gargantuan scale, exacting requirements, and homogenizing infrastructure of hard technologies does not offer such pluralism. Only our largest conglomerations of resources, shielded by the powers of the state from the vagaries of the economic and political marketplace, can perform such demanding tasks. Analogously, on an international level the risks of the hard path, such as accumulation of carbon dioxide [65] or misuse of strategic materials (see Appendix III), are so formidable that only supranational coercion can reduce them, so abridging national sovereignty and freedom of choice. (People who consider this a good idea in the abstract are often reluctant for it to happen to them at a national or personal level.)

One could argue forever whether the structure of the energy system is a cause, effect, or concomitant of social structure. [66] Obviously, other influences on social structure, such as information flows, water flows, and land tenure, are important (though often related to the energy system). The skein of causation is thoroughly tangled, and I do not wish to appear simplistic. But it seems undeniable that, for example, energy decisions can and do affect the spatial distribution of jobs, hence of settlements,[25] hence of political power. That is, energy decisions, not only at the point of resource extraction (e.g., the stripping of coal in Wyoming's Powder River basin) but at the point of conversion and use, are unavoidably land-use and regional decisions, just as the railroads once shaped our land-use patterns. One could at least argue, too, that the extreme capital intensity of new energy systems requires end use to be nearly optimized in an economic sense, so that its nature and patterns conform to the needs of the source of supply rather than the other way around. (I favor peak load pricing, for example, and possibly such measures as ripplesignal load control for some applications; but one can hardly pretend that load-management techniques [18] are not intended to alter the patterns of use and in some sense—one of which undersized solar water heaters are often accused—to alter the consumer's life style.)

Centralized energy systems are also inequitable in principle because they separate the energy output from its side-effects, allocating them to different people at opposite ends of the transmission lines, pipelines, or rail lines. The export of these side-effects from Los Angeles and New York to Navajo country, Appalachia, Wyoming, and the Brooks Range (not to mention Venezuela, the Caribbean, Kuwait, and British Columbia) makes the former more habitable and the latter more resentful. That resentment is finding political expression, As the weakest groups in society, such as the native peoples, come to appear to stronger groups as miners' canaries whose fate foretells their own, sympathy for the recipients of the exported side-effects grows.

Throughout the world, central government is trying to promote expansionist energy policies by preempting regulatory authority, and in the process is eliciting a strong State (or Provincial) and local response. Washington, Ottawa, Bonn, Paris, and Canberra are coming to be viewed locally as the common enemy. Unholy alliances form. Perhaps Montana might mutter to Massachusetts, "We won't oil your beaches if you won't strip our coal." As Congress—made of State people with no Federal constituency—increasingly molds interregional conflict into a common States'-rights front, decisions gravitate by default to the lower political levels at which consensus is still possible. At those levels, further insults to local autonomy by remote utilities, oil companies, banks, and Federal agencies are intolerable. Thus people in Washington sit drawing reactors and coal complexes on maps, but the exercise has increasingly an air of unreality because it s overtaken by political events at the grassroots. The greater the Federal preemption (as in offshore oil leasing), the greater the homeostatic State response. The more the Federal authorities treat centrifugal politics as a public relations problem, the more likely it becomes that they will not only fail to get their facilities sited, but will also in the process destroy their own legitimacy. To some extent this has already occurred, and I have no doubt that States will soon gain a veto power, at least, over nuclear facilities in their jurisdiction (as pending Federal legislation proposes). On this issue, as in other spheres, the traditional linear right-left political spectrum seems to become cyclic as differently grounded distastes for big government merge across gaps of rhetoric. The resurgence of individual, decentralized citizen effort in politics, as in private life and career, seems to me an important political universal in most industrial nations today. [67]

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[25] Nietzsche remarks that cities that have not decided what they want to be tend to grow to unnautural size. Rome in its glory was slight compared to Athens, for in Rome the energy that should have gone into the flower went instead to make the stem and leaves, and hence was of no consequence. It is a sobering perspective for modern planners who move industrial complexes around on a map like chess-pieces on a board.

Big Brother does not like losing his grip. Only last year, for example, some Federal officials were speculating that they might have to seek central regulation of domestic solar technologies, lest mass defections from utility grids damage utility cash-flows and the State and municipal budgets dependent on utility tax revenues. Since utilities are perceived as having too much power and utility regulators too little sensitivity already, a surer recipe for grassroots revolt would be hard to imagine. I think perceptions of the value of dependence on utilities are shifting rapidly as the enterprise reaches such a size that it starts to intrude on life in many traditionally "safe" areas, as in Ontario, or as its vulnerability becomes painfully manifest, as in England, or as general political consciousness rises in step with utility bills. The disillusionment and resentment I see in many industrial countries are akin, perhaps, to that of a citizen of a poor country who is realizing that an energy technology predicted to bring him self-reliance, pride, and the development of his village has actually brought him dependence, a cargo-cult mentality, and the enrichment of urban elites. I believe the recent shift of institutional and individual investment away from utilities reflects not only concern with debt structure and interest coverage but also, more fundamentally, with gradual withdrawal of legitimacy by a fickle public that has already done the same to major oil companies. I believe further that the grounds of this shift among a previously tolerant, even supportive, public are structural, arise essentially from suspicion of centrism, and would not be reversed by nationalization or rechartering that ignored scale.

Living in England, I am keenly aware of the vulnerability of an energy system that permeates the end-use structure, distributing a form of energy that cannot readily be stored in bulk. Its supply relies on hundreds of large and precise machines rotating in exact synchrony across a continent, strung together by a vast web of frail arteries that can be severed with a rifle. Disruption can be instantaneous and pronounced, so much so that English users have gone to very costly lengths to protect themselves, reportedly installing more private than public capacity in some recent years. The vulnerability of the grid is enhanced not only by the guerrilla activity [68] current in Britain but also by the capital intensity of the grid. In the United States, a power station requires roughly a quarter of a million dollars' investment per direct job. Correspondingly low labor intensity and technical specialization mean that political power resides in fewer and fewer workers whose highly developed skills may be matched by coherent purpose and organization. Most power engineers appear to have an admirable sense of dedication to the public good. In Britain, however, a leader of the power engineers remarked recently—and correctly—that "the miners brought the country to its knees in 8 weeks; we could do it in 8 minutes." His union, before starting a recent round of wage negotiations, even proposed a 24-hour initial strike as a token of sincerity. In this sphere as in the military sphere, the nature of a technology has fundamentally altered the power balance between large and small groups, [68] making it less tolerable for potentially hostile or abnormal people to enjoy traditional civil liberties, and generally increasing the level of suspicion and intolerance in society. "Power to the people" now makes us ask: [60] "Power to *which* people?"

Such political costs, prominent in the list of nuclear power issues, correspond to analogous costs of possessing military nuclear weapons: indeed, the latter costs may have helped to sensitize us subliminally to the former. For example, nuclear weapons demand an elite, self-perpetuating cadre that will meticulously and perpetually guard and prepare the weapons, isolated alike from social unrest and from proximate (effective) political accountability, rather like Weinberg's concept of a "technological priesthood" for guarding long-lived nuclear wastes. [3] Nuclear weapons demand a fast-reacting central authority that can make decisive and timely military responses without the niceties of balanced democratic consultation, just as nuclear power tends to weaken political responsibility through centrism. Further, the power of nuclear weapons requires that willingness to use them be periodically demonstrated obliquely—by fighting small nonnuclear wars as theater, [70] not to attain classical military objectives so much as to present an image of united national will. This image may require public dissent at home to be suppressed, or prevented by deception, [70] and thus contributes both to loss of public candor and trust and to the evolution of an executive siege mentality—events with an obvious parallel in the civilian sector. In several fundamental ways, then, the military imperatives of nuclear weapons conflict with the political imperatives of a free society. I suspect that latent public unease with this conflict is an important indirect element in the political climate [71] in which opposition to official siting proposals can flourish.

Akin to this problem, but less visible in public is the array of pressures on individual high technologists. [1] Intense social pressure within committed institutions tend to discourage deviance from shared values and beliefs, reinforcing them with apparent consensus (deserved or not) even at the expense of personal ethics. It is well known that people in groups, even with high intentions, do things they would never dream of doing individually; and our professions have not yet devised ways to shield the delicate spirit of inquiry and dissent from subtle (or even not so subtle) peer pressures. Even at Oak Ridge National Laboratory I know of instances where the public and private views of fine technologists perforce must differ, so corroding both personal and technical quality. Shifting one's career to a field that one can have good dreams about may not be an attractive option: so long as Federal R&D interest is perceived to be mainly in hard technologies, good technologists will be reluctant to shift to soft ones, thus limiting the long-term ability of those sectors to absorb funding effectively and further reducing their attractions. This is a practical demonstration of the exclusivity of paths. [1]

The big organizations needed to develop big technologies suffer often from fuzzing of responsibility. So many people contribute to a project that nobody is really responsible, [72] and responsibility in the traditional engineering sense may slip through the cracks. But more destructive to technical quality is the tendency of such big organizations, after the exciting surge of initial pioneering, to become routine and deadly serious. For that reason alone—to say nothing of public controversy—fission is now no fun any more; therefore it will not be done well; therefore it has failed.[26] A subtle but important disadvantage of big technologies (as Freeman Dyson points out) is that they are so big that one cannot play with them, so an essential breath of both fun and creativity is lost. In contrast, soft technologies bring out the ingenious tinkerer, the spirit that made the sophisticated (but understandable) gadgets that fill any good farm museum. The challenge of simplicity, the art of artlessness, have full scope. Human scale relative to the technologist himself lets ingenuity—the source of paper solar collectors, heat cables, [73] and exterior retrofit insulation [74]—expand far beyond the narrowly focused limits attainable in hard technologies.

A further institutional problem from which soft technologies are nearly exempt is control of potentially hazardous developments. Soft technologies are by definition nonviolent. Hard technologies are often Siamese twins of weapons (see e.g., Appendix III, or consider solar-satellite schemes or laser fusion). Worse, subjecting civilian or quasi-civilian hard technologies to the necessary political control may require, for informed discussion, the release of information that endangers the public. For example, to provide a basis for intelligent decision-making about LMFBR disassembly accidents, one must at the same time reveal a good deal about how to design atomic bombs. In order not to be faced with the unpalatable choice between endangering the public by releasing information useful to the malicious and, on the other hand, ceding decision-making on a crucial matter to an elite [75] and so sacrificing democratic principles, one may have to head off such technologies as soon as such a choice appears on the horizon. To do this effectively, one may be forced to try to suppress lines of research that are still in the realm more of science than of technology. This in turn raises unpalatable issues of liberty vs license in academic freedom: a controversy now raging in genetic research, which is in some ways analogous to the state of nuclear science in the 1940's. Such encroachment is less likely to be considered or needed at all if we channel our efforts into less exploitative, more adaptive, gentler technologies.[27]

I have sketched a few examples of the labyrinthine complexity with which energy policy questions (to say nothing of their consequences) ramify into every aspect of our lives. The policy questions that the soft path makes so prominent raise also some more basic structural and philosophical questions that we can neither answer definitively nor ignore: questions of the personal values within which, and the social ends for which, energy is sought. My earlier sketch [1] of a few of these questions—economic growth and its diseconomies, distributional equity, transindustrial values—may need expansion here.

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[26] One can likewise argue that really well-engineered nuclear facilities will be so boring to operate that talented people will seek other careers. Some observers see this as a major long-term problem at facilities like the reprocessing plant being build at Barnwell, S.C.

[27] A simple example from E. Robertson: There are three ways to make limestone into a structural material. We can cut it in blocks, or we can bake it at thousands of degrees into portland cement. Or—most elegantly—we can feed chips of it to a chicken. Twelve hours later it emerges as eggshell, several times as strong as the best portland cement. Evidently the chicken knows something we don't about ambient-temperature technology.

A cursory glance at a graph of U.S. per-capita primary energy since, say, 1880 dispels any notion of a significant correlation with social welfare on a time scale of decades. The graph remains flat for several long periods when welfare by almost any measure improved significantly, then rises steeply during the 1960's out of all proportion to real improvements. Nonetheless the existence of a close correlation—even an ironclad causality—is an article of faith to many who measure our success by the quantity of goods and services consumed, rather than by how far we achieve human satisfaction, joy, and inward growth with a minimum of consumption (the concept central to Schumacher's classic essay [12] on Buddhist economics). The former view is consistent with the industrial-era paradigm in which, as Mumford caustically observes, [76]

> All but one of [the seven deadly] . . . sins, sloth, was transformed into a positive virtue. Greed, avarice, envy, gluttony, luxury, and pride were the driving forces of the new economy . . . Goals and ends capable of working an inner transformation were obsolete: mechanical expansion itself had become the supreme goal.

As a result of this process, as Diesing notes,[77]

> One cultural element after another has been absorbed into the ever-widening economy, subjected to the test of economic rationality, rationalized, and turned into a commodity or factor of production. So pervasive has this process been that it now seems that anything can be thought of as a commodity and its value measured by a price . . . time, land, capital, labor; also personality itself, . . . art objects, ideas, experiences, enjoyment itself, and even social relations. As these become commodities they are all subject to a process of moral neutralization.

The very language that weaves our thoughts about the world is thus conditioned by an economic paradigm that treats means as ends [78] and places goods above people.[12] But the cult of material acquisitiveness underlying our assiduously promoted image of the good life has its flaws, and we are coming to see them more clearly.

For example, we concentrate our resources not on microefficiency or resilience but on managing our growth and resolving its numerous conflicts and inequities. So we weave a web of bigness and of incomprehensive, unmanageable complexity. But are we sure that our transaction costs do not exceed our productivity? Is it worthwhile, or possible, to go on like this? Miles states a related thesis thus.[79]

> (1) The more energy a society uses, the more interdependent it tends to become, both within itself and in relation to other societies.
>
> (2) The more interdependent a society becomes, the more complex it becomes, and the more man-designed and man-controlled its economic, ecologic, and political systems and subsystems become.
>
> (3) The more complex and interdependent the systems and subsystems, the more vulnerable they become to design failures, since:
>
> (a) No human designers, and this applies especially to the politicans who are responsible for designing the largest human systems, can know or comprehend all the factors that need to be taken into account, and their interrelation, sufficiently to make the current set of systems work well. If complexity and interedependence increase further, the problems will be further compounded.
>
> (b) Those responsible for selecting the designers—the voting public in a society like the United States—are even less informed about the intricacies of the systems than the politicians who represent them. They cannot judge, therefore, which programs or social designers (politicians) to support, and in consequence they are highly likely to vote for the representatives who promise to support programs that benefit them disrectly and immediately—a fatal flaw in designing workable complex systems for interrelating enormous numbers of human beings with each other and their environments.

(4) The United States is probably nearing the point (it could even be beyond it) where the complexity of the systems of interdependence exceeds the human capacity to manage them, causing system breakdowns to occur as fast as, or faster than, any combination of problem-solvers can overcome them.

(5) World systems of interdependence are more remote, inefficient, and precarious than national systems, and may have exceeded their sustainable level of complexity. More and more nations are looking for ways of becoming more independent, rather than more interdependent, even if to do so they will have to be satisfied with a lower standard of living. Those social analysts who have asserted that we will inexorably continue to move upward toward higher levels of technology, higher levels or energy consumption, greater volume of international exchange of raw materials, goods, information, culture, and tourists may be in for a surprise. Humanly designed and operated systems have upper limits of complexity, and when they reach those limits or complexity, they simply break down.

Here is another conundrum. Assuming that people seek to escape from repugnant work into blissful leisure, we strove mightily to mechanize, automate, and fragment work. But while that effort at first relieved mindless drudgery, it soon came to deprive people of meaningful roles, even of jobs themselves. As the craftsperson working creatively with tools was displaced by the machine demanding a stultified operator, people, especially those whom age or sex or ability ill-suited for economic roles, were deprived of a share in a visible and widely shared public purpose. We systematically substituted money and energy for people. We redefined work as obtaining a commodity (a job) from a vendor (an employer), substituting earning for an older ethic of serving and caring. Thus alienation in place of fulfillment, inner poverty alongside outward affluence, a pathologically restless and rootless mobility, became the symptoms of a morbid social condition that corroded humane values. Our brilliant success in achieving economic goals has thwarted the human goals of much of our population by declaring their lives to lack value. Might not happy people (in D. T. Suzuki's phrase) instead enjoy life as it is lived rather than trying to turn it into a means of accomplishing something else? Our sense of the whole, in personality and family as in community and country, has been sacrificed to specialization and mobility, the imperatives of efficient production. But is that price worth paying? Soft-technology life near enough to the soil to understand the life process has nurtured every previous culture, [80] and for all its hardships in the past—many of them now avoidable—it has a cultural value. Are we sure that by rejecting that awareness of the life process and turning ourselves into mere cogs of mechanical production we are not losing something essential to the human psyche and to our own mythic coherence?

Again, if we work to buy a car without which we cannot get to work, is the *net* benefit so very substantial? Is not this circularity a measure less of our wealth than of our failure to create fulfillment with an elegant economy of effort and time? Illich [13] cites a number which, whether it is quite correct or not, still conveys an important idea: He says that the average American man drives about 7,500 miles a year in his car, but that the total time it takes him to do this and to earn the money to finance it is about 1,500 hours, which works out to 5 miles an hour, and we can walk nearly that fast.

Again, 3 billion people offer living refutation of a theory that assured us that our growing wealth would automatically enrich the poor without our having to redistribute anything. We are waking up: In the famous Harris poll of late 1975, a solid 61 percent felt it is "morally wrong" for Americans to consume such a disproportionate share of the world's resources, and 50 percent worried that a continuation of such behavior will "turn the rest of the world against us." Yet the theory persists: Appeals for more electricity with which to help the poor still come from utilities that have long charged the poor several times as much as the rich (or profligate) for the same unit of electricity.[28] Yet we can now calculate that raising, say, the poorest three-fifths of Americans to the per-capita energy level of the rest would not require massive energy growth, but rather a level well below any current official projections. Even more significantly, we can now see that reducing ourselves to the "primitive" energy level of most Europeans need not reduce our material comforts at all and could markedly improve the quality of life. [15]

As we learn to question the ability of present policy to serve both public and private ends, the legitimacy of those ends themselves comes up for review. Our know-how has far outstripped our know-why; and as we seek to reverse the balance, old political concepts begin to reassert themselves. Grassroots democracy acquires [67] a more concrete meaning. Jefferson and Mao gaid a curious affinity. Control of property and land—a cornerstone of free-enterprise democracy—comes to embrace control of the energies essential to life, liberty, and the pursuit of happiness, for to control those energies we must now control the land they lie under or fall upon. In the process we may start to approach Aldo Leopold's land ethic, or even the native American concept[29] that absolute, monopolistic ownership of land, at first incomprehensible, is in a sense blasphemous.

In our dynamic, pluralistic culture, our decisions will be made at the points of tension between competing value systems. Some of these tensions have long been with us but are now taking on a new significance. For example, for many historical reasons (including the forces that selected those who emigrated here), it is a basic tenet of American social philosophy that economic and social activity are primarily to serve private and individual, not public and communitarian, ends. Public ends are indeed conceived not as abstract moral universals, such as making a good or a just society, but rather as a pragmatic summation of diverse private ends. This value structure, this very individualism that has enabled us to accomplish so much materially, has nurtured the primacy of economic and technological values over spiritual and humanistic ones, and has long kept us from coming to grips with our own Tragedies of the Commons (Garrett Hardin).

As "economic growth and technical achievement, the greatest triumphs of our epoch of history, [show] . . . themselves to be inadequate sources for collective contentment and hope" (Robert Heilbroner), we are starting to appreciate that we have no monopoly on wisdom. If we can suspend our cultural arrogance, we may learn much from other peoples with different values. We may, for example, be surprised and much moved to hear the chiefs of the Micronesian island of Maap threatened by a Japanese hotel complex, petition us thus: [82]

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[28] Here equity and narrow economic arguments [27] may conflict. The broader question of energy price is vexing. Unlike many colleagues, I do not consider energy prices an appropriate instrument of distributional equity. Energy should be properly priced, and if poor people cannot then afford it, they should be made less poor in ways that do not entail giving cheap energy to rich people. Of course, we may wish to direct to good social purpose the windfall profits that higher prices may otherwise give to oligopolies; but that is a separable problem that should not be beyond our wit to solve.

[29] This is not a new theme. "Moreover the profit of the earth is for all: the king himself is served by the field. He that loveth silver shall not be satisfied with silver; nor he that loveth abundance with increase: this is also vanity. When goods increase, they are increased that eat them: and what good is there to the owners thereof, saving the beholding of them with their eyes? The sleep of a laboring man is sweet, whether he eat little or much: but the abundance of the rich will not suffer him to sleep."—Ecclesiastes 5:9–12.

> Whereas we love our land and the ways in which we live together there in peace, and yet live humbly and still cherish them above all other ways, and are not discontent to be the children of our fathers. it has become apparent to us that we have been persuaded to subscribe to processes that will quickly extinguish all that we hold most dear. We, pilungs and langanpagels, elders and elected officers, Chiefs in Council of and on behalf of all the people of the Eighteen Villages and Fiefs of the island of Maap . . . declare our love of this place and of the ways passed down to us by the generations. We have inherited from our fathers a land that is lovely and provides for us the fruits of the earth and of the sea. We are few in numbers but have a brave history and are strong in our resolve to preserve these things that are sweet to us and freely to determine the affairs of our island with respect to custom and deference to the law . . . We . . . now urgently and passionately unite . . . to ask the help of . . . [others] in ridding us of this invasion and freeing us, that we do not become servants in our own land, to choose for ourselves the paths that will be good for the people of all the villages of Maap. [W]e meet today under the shadow of . . . change and innovation and . . . we know our people to be roused against these things, as they today do forcefully convey through a petition . . . [W]e are therefore all the more solemnly moved to affirm our united will in the face of the unfamiliar contingencies of this age and the ages to come, so that our home may not be vulnerable to the casual invasions of those who do not know our hearts or the disloyal speculations of those who do.

ACKNOWLEDGMENTS

Such language, so reminiscent of our own national beginnings, must remind us of the power of ideas—republican government in monarchical Europe, or Christianity in Rome—to transform societies with extraordinary speed. The thesis that we stand today on the verge of such a transformation must command attention, [5] and accounts for much of our present failure of public discourse. As Willis Harman [72] points out, different people with similar perceptions of reality may have different interests, and our society has mechanisms for resolving conflicting interests, but we have no mechanisms for reconciling different perceptions of reality, or even for recognizing their divergence as a basis of conflict and misunderstanding. It is perhaps encouraging, then, that the concept of a soft energy path brings a broad convergence that, even as it conicides with many preexisting strands of social change, cuts arcoss traditional lines of political conflict. It offers a potential argument for every constituency: civil rights for liberals, States' rights for conservatives, availability of capital for business people, environmental protection for conservationists, old values for the old, new values for the young, exciting technologies for the secular, spiritual rebirth for the religious. As we realize, in Alwyn Rees's, phrase, that when we have come to the edge of an abyss, the only progressive move we can make is to step backwards, we begin to see that we can instead turn around and then step forwards, and that the turning around—the transition to a future unlike anything we have ever known—will be supremely interesting, an unprecedented central project for our species.

Faust, having made a bad bargain by not reading the fine print, brought disaster on innocent bystanders (Gretchen's family). Still, he was eventually redeemed and accepted in heaven because he changed his career, redevoting his talents to bringing soft technologies to rural villagers. That choice of "the road less traveled by" made all the difference to him; and so it can to us, for underlying the structural differences between the soft and hard paths is a difference of perceptions [3] about mankind and his works. Some people, impressed and fascinated by technology's glittering achievements, say that if we will only have faith in human ingenuity (theirs) we shall witness the Second Coming of Prometheus (if we have yet recovered from the First), bringing us undreamed-of freedom and plenty. Other people say we should plan on something more modest, lest we find instead undreamed-of tyrannies and perils; and that even if we had a clean and unlimited energy source, we would lack the discipline to use it wisely. Such people are really saying, first, that energy is not enough to solve the ancient problems of the human spirit, and second, that the technologists who claim they can satisfy Alfven's condition that "no acts of God can be permitted" are guilty of hubris, the human sin of divine arrogance. In choosing our energy path we have an opportunity—perhaps our last—to foster in our society a greater humility, one that springs from an appreciation of the essential frailty of humankind.

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Neither this paper nor reference 1 could have been written without the generous and tolerant hospitality of Ann and Henry Kendall and of the staff of the Appalachian Mountain Club's Pinkham Notch Camp. I am deeply grateful to them all.

APPENDIX I: METHODOLOGICAL NOTE

Present policy rests on the belief that the future is essentially the past writ large. Quantitative assumptions, such as rates of growth in primary energy demand or in GNP, are extrapolated by so many percent per year—i.e., inherently exponentially—changing according to historically observed patterns (elasticities, saturations, etc.) or not at all. Such models have trouble adapting to a world in which, for example, real electricity prices are rapidly rising rather than slowly falling as they used to.[58] More generally, such models have a certain inflexibility that tends to lock us into a single narrow vision of life styles and development patterns. Extrapolations have fixed structure and no limits, whereas real societies and their objectives evolve over decades—i.e., they have slow variables affecting model structure and objective function in a finite world where the key questions are those of choice and value within consecutively approached constraints. Extrapolations assume essentially a surprise-free future even when written by and for people who spend their working lives coping with surprises. Worst, extrapolations are remote from real policy questions. Decision-makers are seldom called upon to fix a growth rate at X or Y percent a year, but rather to apply pragmatic judgment to intricate decisions of detail. If the modeler assumes a single value, or only a few values, for each basic variable, the model may elicit a "my number is better than your number" response; if many values, the model unhelpfully offers the policymaker enough options to keep him undecided indefinitely, so he will simply ignore it. What it does not offer him is a sense of the goals and criteria that would make some numbers preferable to others.

Having diagnosed these defects (set out in a 1974 occasional paper for the Aspen Institute for Humanistic Studies), Monte Canfield, Jr., and colleagues in the Energy Policy Project of the Ford Foundation developed several scenarios that are policy-oriented descriptive, (not prescriptive), exploratory, and adaptive. They are defined not by exogenous numerical assumptions but rather by policy goals and mental models presumed to prevail among governments and their constituencies. A reader can thus identify that scenario that most nearly reflects his own frame of mind, note its consequences, and gain a fuller understanding of the consequencies of his own everyday choices. Scenarios are also easier than extrapolations to test for resilience in the face of surprises—important in an era when discontinuities and singularities may matter more than the fragments of secular trend in between.

This scenario technique is valuable and should be extended, just as extrapolation, in skilled hands, has its uses in short-term forward planning (especially when bolstered by multivariate sensitivity analysis) and has rightly had much talent devoted to its refinement. But I believe both techniques must be supplemented by a third method that highlights what can be done in the long term by recommitting resources in the short term. This method is the broad-brush "working-backwards" policy exploration exemplified by reference 1 and by the Canadian [19], Danish [3, 10], and Japanese [3] studies it cites. Such an exercise should use a time frame long enough to make major supply changes and turn over major capital stocks: I normally use 50 years, about the lifetime of a power station ordered today. I also do not pretend to achieve econometric precision (which often seems spurious anyway), nor try to simulate markets and prices decades ahead, but instead estimate main terms in the spirit of experimental physics, striving not for elaborate sophistication but for transparent simplicity [1, 19]. (See my discussion of fossil fuel costs for why I use capital intensity as an a posteriori signal rather than market equilibrium as an a priori mechanism.) I argue elsewhere [1] that working backwards, by turning divergences into convergences, provides insights unavailable to anyone working forwards. One can then work forwards, or both ways at once, to devise transitional tactics.

Studies of soft energy paths or of related topics, using methods akin to those of reference 1, are in progress (generally with very limited resources) in at least the following centers with which I am in touch via the main researchers shown:

United States: Union of Concerned Scientists, Cambridge, MA (Prof. Henry Kendall) Institute for Energy Analysis, Oak Ridge, TN (Dr. Alvin Weinberg) Center for Environmental Studies, Princeton University (Prof. Robert Williams) Energy & Resources Group, University of California, Berkeley (Prof. John Holdren)

Canada: Science Council of Canada, Ottawa (Dr. Ray Jackson) Ministry of Energy, Mines, & Resources, Ottawa (Dr. Peter Dyne) Energy Probe, University of Toronto (Mr. Barry Spinner) Premier's Office, Charlottetown, P.E.I. (Mr. Andy Wells)

UK: Friends of the Earth Ltd., London (Mr. Walter Patterson) International Institute for Environment & Development, London (Mr. Gerald Leach) Energy Research Group, The Open University, Milton Keynes, Bucks. (Dr. Peter Chapman)

France: Faculté Sciences Economiques, University of Grenoble (Dr. J.-M. Martin)

Netherlands: A dispersed group (Dr. Eric-Jan Tuininga, TNO, Apeldoorn; and Dr. Kees Daey Ouwens, Rijksuniversiteit Utrecht)

Norway: Råd for Natur- og Miljøfag, Universitetet i Oslo (Dr. Paul Hofseth)
Denmark: Niels Bohr Institutet, København (Dr. Bent Sørensen)
EEC: Technical University of Denmark, Lyngby (Prof. Niels Meyer)
Sweden: Future Studies Group, Stockholm (Dr. Måns Lönnroth)
Austria: International Institute for Applied Systems Analysis (Dr. Wolf Häfele; also active in West Germany and other countries)
Israel: Weizmann Institute of Science (Dr. Tullio Sonnino)
New Zealand: University of Auckland (Dr. Robert Mann)

Finally, energy studies cannot hope to succeed in isolation. The energy problem is intimately related to all the other great issues of our day, and is arguably only a symptom of deeper social disorders that any energy strategist must address. Thus when I suggest [1] that "The most important, difficult, and neglected questions of energy strategy are not mainly technical or economic but rather social and ehtical," I am not thinking only of social and ethical *energy* issues. Caldwell sums it up. [66] "The energy crisis is a natural product of the sociotechnical system that it now threatens."

APPENDIX II: TEMPERATURE SPECTRUM OF PROCESS HEAT

Nearly one-fourth of all U.S. primary energy is devoted to process heat in industry (Table 1). Its temperature distribution is the main unknown in constructing a rough thermodynamic classification of end-use energy, as in Table 2.

Before 1976, the only attempt of which I am aware to construct a modestly detailed spectrum or histogram for U.S. process heat was an unpublished study by Westinghouse Electric Corp. that gives five temperature categories for 15 process sectors [1] in 1972. I do not know the conventions or methodologies used. The "fossil fuel uses" (10^{12} Btu) are shown as follows in the summary table.

Industry	230°F	231°–400°F	400°F and steam drive	Electric generator	Space heat	Total
Process	2,363	2,944	13,641	732	1,063	20,743
Other	708	471	590	24	564	2,357
Total	3,071	3,415	14,231	756	1,627	23,100
Percent	(13)	(15)	(62)	(3)	(7)	(100)

These figures, however rough, suggest that it would be useful to confirm how much heat is used at low and moderate temperatures in industrial processes.

Two studies nearing completion for the ERDA Solar Division (Mr. William Cherry, project manager), to be published in early 1977 by the National Technical Information Service, are exploring the economic and engineering parameters of solar process heat, and in the process are developing a temperature spectrum of industrial process heat in the United States. The two contractors, working independently at ERDA's request, are InterTechnology Corp. (ITC) (Warrenton, VA) and Battelle Columbus Laboratories (BCL). Mr. Malcolm Fraser of ITC and Dr. Elton Hall of BCL have generously sent me early versions of their data, which are incomplete, preliminary, subject to revision, but nonetheless very interesting.

Mr. Fraser summarized interim ITC results in his Survey of the Applications of Solar Thermal Energy to Industrial Process Heat, given at the Sharing the Sun Conference, International Solar Energy Society, Winnepeg, Aug. 15–20, 1976. He stressed that:

". . . the survey was performed from the point of view of process requirements rather than the point of view of current methods of using heat. Thus, the temperature of major interest for a particular application was the required temperature of the process material rather than the temperature at which the heat is currently provided. Currently much heat of high thermodynamic availability is wasted because it is used for a low-temperature application which could readily be satisfied with lower-temperature heat. Fuels with the capability of a flame temperature of

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[1] Food and kindred products; textile mill products; apparel and other textile products; lumber and wood products; paper and allied products; chemical and allied products; petroleum and coal products; rubber and plastic products; stone, clay, and glass products; primary metal industries; fabricated metal products; machinery, except electrical; electrical equipment and supplies; transportation equipment; natural gas processing.

2,000+°F are burned with the ultimate objective of making hot water, for example. A solar process heat system should be designed to satisfy the needs of a process and not merely to substitute for the current method of providing heat."

The ITC survey is exceedingly detailed. Of the more than 450 four-digit Standard Industrial Classification groups in mining and manufacturing, ITC selected more than 100: mostly those that used over 5,000 GWh(t) of direct fuels in 1972, plus some others required "to obtain a broad-based coverage of industry." This sample uses about 70 percent of all industrial direct fuel. For each industry, ITC constructed process flowsheets showing process, temperature, and amount of non-electric heat needed for specific applications, then integrated the results into a temperature spectrum (Figure A). The preliminary spectrum here includes some 67 four-digit SIC groups (and over 170 specific processes) using a total of 7.2 quads/year, or about 48 percent of the estimated total use of process heat in industry in 1972. ITC believes the final (larger) data base will not yield radically different curves than this interim sample.

In terms of terminal temperature, about 5 percent of the heat load is below 100° C and about 24 percent below 177° C. But if the heat required to preheat from ambient is also considered—for it "should be possible to visualize a method of utilizing preheat [e.g., from solar sources] in essentially every application"—these figures change to about 28 percent and 42 percent respectively, as shown in the upper curve of Figure A. These proportions are the basis of the process heat classification used in Table 2, whereas preheat is neglected in the temperature distribution mentioned in reference 1.

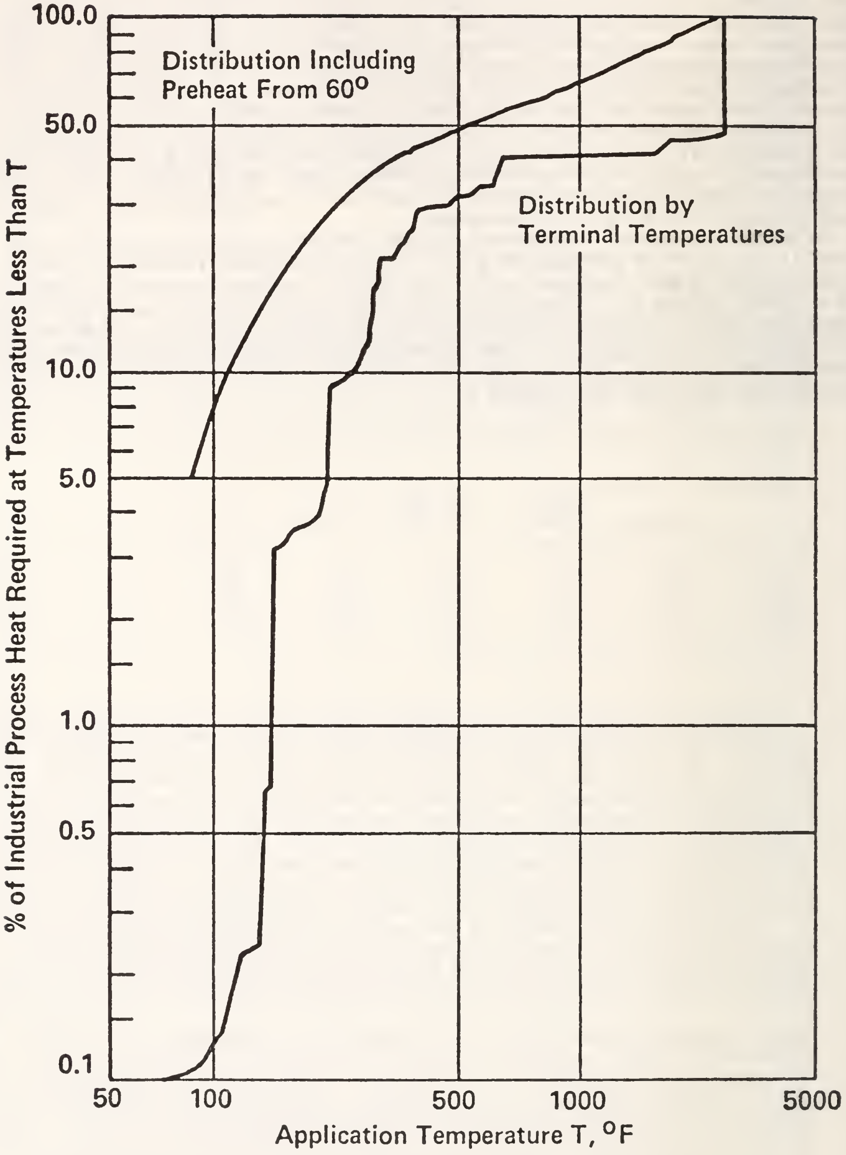

Figure A. Preliminary, Incomplete Data of Inter-Technology Corporation Cumulative Distribution of Process Heat Requirements.

The BCL data, which use the same process-oriented approach, appear less detailed and at an earlier stage of development. The preliminary results of process analysis of an incomplete sample (7.87 quads), and of a less fine-grained and less precise statistical analysis of a larger sample, are as follows (direct fuel, quads/year, ca. 1975):

Category	Process analysis	Percent	Statistical analysis	Percent
<100°C (<212°F): Total	0.27	(2)	0.26	(3)
Hot water	0.07		0.12	
Direct heat or hot air	0.1		0.14	
100–177°C (212–350°F): Total	1.34	(17)	3.25	(32)
Steam	1.2		2.6	
Direct heat	0.14		0.65	
>177°C (>350°F): Total	6.35	(81)	6.53	(65)
Steam	0.5		0.56	
Direct heat	5.85		5.97	
Grand total (rounding errors not corrected)	7.86	(99)	10.04	(100)

The sample in the right-hand column reportedly includes about 80 percent of all process heat; the rest is in unexamined small industries with unknown temperature distribution.

The BCL data thus show 2 to 3 percent of process heat; below 100° C and a cumulative total of 19 percent (by process analysis) or 35 percent (by statistical analysis) below 177° C. In view of the inherent uncertainties and limited samples used, the data seem reasonably consistent with the ITC data if the BCL data are assumed to reflect terminal temperatures without regard to preheat from ambient. The greater detail of the ITC data base, however, leads me to prefer it as a basis for Table 2. More useful comparisons will of course be possible once the reports are both published around early 1977.

Appendix III: Supplementary Notes on Nuclear Proliferation

The brevity of reference 1 leaves several points to be qualified or expanded in this more technical companion-piece,

First, a tacit premise of my argument [1] is that civilian nuclear technology is a principal driving force behind the proliferation of nuclear weapons today. This case has been made in detail by other authors [83–88]. I need not reiterate here the role of civilian power reactors in spreading knowledge, hardware, and expectations and in reducing the time and the political leap needed to convert latent to actual proliferation. It is also obvious that the intended or actual possession of civilian nuclear facilities, because of their military potential, is a destabilizing psychological influence that may impel neighboring countries to seek a similar potential.

A more disturbing and little-known aspect of civilian nuclear power programs, however, needs to be spelled out here to combat a widespread misconception that I shared until recently. It is a delicate subject, but I believe the only thing more dangerous than talking about it would be not talking about it.

It is well known that reactor-grade plutonium (exposed to high neutron flux, hence relatively high in concentration of isotopes of high spontaneous fission rate such as plutonium-240) is not ideally suited to making explosives. It is now widely conceded that such plutonium can be used by terrorists, on the basis only of the extensive information in the open literature [88–91], to make crude bombs of low and unpredictable yield (but still sufficient to wipe out a government, breach the containment of a nuclear facility, etc.). It is also known that a higher yield with rather narrow dispersion can be obtained by using sophisticated techniques unlikely to be available to amateurs. This second fact has so far been largely ignored, since traditional concerns in this area have focused on what terrorists can do. It has been frequently assumed, therefore, that governments wishing to make bombs would either juggle civilian fuel cycles to obtain low burnup (probably evading international safeguards) or, more likely, make "dedicated facilities," probably clandestine, specifically to generate weapons-grade plutonium. However, my considerations of this problem have led me to conclude that the techniques likely to be available even to small, modestly sophisticated governmental weapons programs—essentially the same techniques that such programs would be likely to use anyhow—would permit reactor-grade plutonium to be used directly in bombs of substantial military utility. Yields could be made quite predictable and well into the kiloton range, though for many such applications nuclear testing would be important (if not essential).

It is difficult to make a technically satisfying but unclassified statement of these matters. Never having received classified information, I am not as constrained as those with expert knowledge. Nonetheless, if any conclusions based on the open literature are correct—and they are shared by some professionals—they place a very different complexion on civilian nuclear programs. These programs are expected to accumulate very large inventories of reactor-grade plutonium very rapidly in many countries. [83] If, as I believe, this plutonium can be used directly to make military bombs while still maintaining high performance, then the civilian stocks appear in a different light—a problem much more prompt, and orders of magnitude larger, than the stocks that might otherwise be created covertly in dedicated facilities.

Reference 1 describes a package of initiatives that, if the United States implemented them simultaneously, unilaterally, and universally, would be likely in my opinion to halt virtually all nuclear power programs abroad. The essential aim of these steps would be to foster an international climate of denuclearization [64, 92] in which it is socially unacceptable—perceived as a mark of national immaturity—to possess or desire either reactors or bombs. Without such a development I see no way to avoid the consequences of endemic nuclear violence, [71] for the technical and political arrangements that must prevent it once the requisite materials are created must last not merely for the usual lifetime of treaties or nations but for the lifetime of the materials themselves—a period many times as long as the period from the Neolithic to the present. The implausibility of success in such arrangements is illustrated by the inability of both Britain [93] and France [94]—perhaps the countries with the greatest experience of exercising political control—to subject their own original nuclear weapons programs to political control or formal decision before those programs were virtually completed.

My thesis that a halt to foreign nuclear power programs under the conditions I describe [1] would go very far to defuse proliferation—i.e., would reduce it by several orders of magnitude, and perhaps ultimately to zero—needs several qualifications. First, if laser enrichment turns out to have tractable engineering and chemistry on a crude pilot scale, then any clever technician should be able, in due course, to make a bomb from a few tons of natural uranium. Uranium ore would become a strategic commodity and we would be back to the Baruch plan. Recent preliminary work by Prof. Allan Krass (currently at Princeton) suggests that the technology is very unlikely to be easier than the research-reactor or theft-and-black-market route to strategic materials. I hope this is correct. Diverse opinions, however, persist, and if there is any chance that some form of laser enrichment will be relatively easy, then our best protection would be to have a fission-free economy in which uranium is not ordinarily mined or traded in international commerce. The quantities needed to make a bomb would then no longer be an undetectable fraction detachable from commercial flows. If there turned out to be no worrying simple form of laser enrichment, we would still have played safe.

Second, there are pockets of technical metastasis that might be relatively impervious to internal and external political pressures resulting from the initiative I suggest. [1] India might be such a place, though I think India is vulnerable to political and economic pressures, especially from within. Nonetheless, India already has bombs and will want to keep them as long as others do. The question is whether India could and would maintain the domestic political, economic, and technical base needed to become an independent nuclear exporter, as well as find qualified client states seeking her exports, all within the political and psychological context I suggest. [1] I consider this implausible and believe that even Indian technical ability would be hard pressed to maintain a substantial domestic program for more than a decade or two in the face of an effective quarantine. Recent demolition of the bizarre idea that nuclear power is a necessary, appropriate, or economically attractive energy source for developing countries [83, 95] makes such secondary metastasis seem even less likely.

Third, research reactors would of course still be a poor country's route to bombs—either by making plutonium in moderate amounts and extracting it in a crude several-bombs-per-year reprocessing plant that might be built [96] in a year or two with perhaps $1 million to $3 million, or else by buying a suitable number of fully enriched uranium cores. Appropriate natural-uranium/graphite research or production reactors are relatively easy to build. [97] This could be made much harder through better international controls and intelligence directed to a few strategic materials such as nuclear-grade graphite, uranium, and deuterium. A more important deterrent or disincentive, though, would be the psychological shifts referred to above, since a country that is not going to have a nuclear power program, in a world that is phasing out nuclear technology, can hardly justify building or keeping research reactors.

I have pointed out elsewhere [98] that nobody has yet thought seriously enough about what the terminal phase of a nuclear economy should look like—i.e., how to phase out nuclear programs in an orderly fashion that minimizes residual hazard. There are some nice technical puzzles here. It is not clear whether reprocessing is advisable or not; nor whether, for example, it might even be worth building some low-power-density reactors specially designed to burn transuranic stocks. Such questions should be addressed by the technical community. I believe, however, that though such technical questions are open, there are grounds [98] for confidence that the institutional barriers to reversing our nuclear commitments can be overcome without prolonged or massive disruption. An appropriate and urgently needed first step widely urged by the arms control community [83, 85, 87, 99]—suspension and stringent reexamination [100] of all plans for reprocessing, recycling, and breeding plutonium—would cause insignificant social or economic disruption and is long overdue. [57, 87]

The political plausibility of the steps I propose [1] is a matter for political judgment. Consistent with many recent declarations in the nuclear trade press, I believe U.S. abandonment of nuclear power is politically plausible within a few years. I am confident that nuclear power is already politically and economically dead [1] in the United States, and am only slightly less confident that its demise may be put in a constructive context [1] closely linked with soft energy policies, strategic arms reduction, and nonproliferation. Looking at European nuclear programs from the inside, I believe the same is true. This may surprise American observers who listen to, say, French and German rhetoric; but to a French or German observer who only reads Presidential speeches and ERDA press releases, the U.S. program might also appear, erroneously, to be easily brushing off a minority fringe protest and going from strength to strength. It is distance, not familiarity, that gives us in the United States our impression of the political and economic robustness of European electronuclear plans (as recent developments in Britain, Sweden, and Denmark attest). Bupp [101] has even been told at the highest levels of the French LWR program that its chance of actually happening—completing most of the reactors currently planned—is perhaps one in three. Surprisingly, the remarkable recent concern in Congress about nuclear export policy is coming to be mirrored in some high French circles, bringing domino-like pressure to bear—ultimately irresistably, I believe—on West Germany. Of course, the commercial enterprises involved have strong incentives, given their cash-flow problems, to recycle EximBank or similar loans [83, 95, 102] via the treasuries of less developed countries into their own revenues; but I believe political revulsion, both public and private, will soon prove stronger.

Our approach so far to nuclear proliferation is all too reminiscent of Paul Ylvasaker's definition of a region as "an area safely larger than the one whose problems we last failed to solve." By treating the civilian and military atoms as distinguishable, and by treating our own possession of bombs as patriotic but others' possession as irresponsible, we have woven a web of hypocrisy [92] and double-think that is as inimical to strategic arms reduction as to control of proliferation. [103] The former, which is the greater and harder problem, cannot be addressed without a new approach to the latter, and the collapse of nuclear power offers us, briefly, the opportunity to do better; but we must stop passing the buck before our clients start passing the bombs.

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35. H. R. Linden, (President, Institute of Gas Technology). Information submitted for the record, House Committee on Science and Technology, full Committee meeting on loan guarantee provisions of HR 3473, ERDA Appropriations Bill, FY 1976, Sept. 18, 1975. Interesting comparative data on escalation and on electric vs. synthetic conversion of coal are included.

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37. D. F. Williams, Applied Energy 1:215–21, 1975 Applied Science Publishers, England; K. D. Bartle et al., Fuel 54:226–35, October 1975, IPC Science & Technology Press, England. The process exposes lumps of coal, without special heating, to solvent vapor above the critical pressure, e.g. toluene at 100 bar. The vapor penetrates between the leaves of carbon and pulls out intact (usually aromatic) molecules by the interstitial hydrogen without cracking them. The hydrocarbons then fall out of the vapor when it is reexpanded in another container; a substantial fraction of the mass of the coal is extracted in a form (typically benzene, anthracene, etc.) whose spectrum is controllable by the solvent, pressure, and exposure time. Virtually all the hydrogen is removed. Metals may be removed too. (nobody knows yet). The residual char (carbon plus minerals) generally melts in the range 100° to 200°C and can be liquid-fed as an underboiler fuel. Like the flash processes, [35] supercritical gas extraction offers the intriguing possibility of small units sited in a coal-using factory; premium fuels extracted on the premises could then be used for kiln firing, for example, and the char for cogeneration and process steam. [40] This flexible scale, simplicity, and lack of tar formation seem to me immensely attractive compared to conventional billion dollar conversion plants.

38. See the citations in reference 1 (notes 26–28); A. M. Squires, Applications of Fluidized Beds in Coal Technology, in J. P. Hartnett, ed., Alternative Energy Sources, in press, Hemisphere, Washington, D.C.; the brochure Fluidized Combustion, Combustion Systems Ltd, 66–74 Victoria St., London SW 1, which is amply illustrated for a nontechnical audience; H. B. Locke & H. G. Lunn, The Chemical Engineer, p. 667–70, November 1975; and the general review by A. M. Squires, Ambio 3, (1), 1–14, 1974. The address of Stal-Laval (GB) Ltd is 41–7 Strand, London WC 2. The domestic fluidized-bed furnace developed by the late Prof. Elliott should be, from the user's point of view, indistinguishable from an oil furnace. Granular coal is delivered by hose from a tank-truck to a bunker, then gravity-fed to a small packaged furnace with very low emissions. Ash is collected in a snapon container akin to a vacuum-cleaner bag, changed at each fuel delivery. The technical problems of such a system appear to be substantially solved, and plans for a U.S. field test are well advanced despite lack of Federal interest outside The Council on Environmental Quality and The Environmental Protection Agency. (In September 1976 ERDA's coal technologists did not appear to have heard of Fluidfire or Stal-Laval, and in April 1976 a leading industrial coal expert told me that Professor Elliott's devices, which I have seen operating, could not possibly exist.)

39. H. Harboe, (reference 1, note 26), citations there and personal communication, 1976. Pilot tests have given Stal-Laval high confidence of success in avoiding blade erosion by sintered ash, largely because the proposed design, rather than striving (like U.S. schemes) for high turbine inlet temperature, limits it to about 800°C, so that sintering, NO_x formation, and volatilization of metallic impurities are greatly reduced. The resulting system, operating at 15–20 bar, attains a First Law turbine efficiency of only 27 percent, but boosts this to over 70 percent (plus any bonus for heat pumps) by taking district heating off the bottom of the cycle. Failure to consider the implications of this design philosophy appears to account for most U.S. skepticism about the readiness of fluidized-bed gas turbines for prompt commercial application. The problem is made still easier by a closed-cycle air bypass (see Harboe & Maude, reference 1, note 26). [41]

40. A detailed Swedish study shows that the marginal capital cost of disbributing electricity for heating Stockholm buildings is nearly twice that of distributing hot water for the same purpose (considering only the capital costs of the distribution networks). The district heating would be done by tunneling tens of meters down in rock, then tunneling up into basements to connect rather than tearing up the streets. The details are given in Utredning om Södermalms framtide värmeförsjörning, met förslag till värmeplan for Södermalm, Stockholms Kommunstyrelse, 1974, and summarized in Neil Muir's informative district-heating paper in the International CIB Symposium (reference 1, note 15).

41. Two very important papers on cogeneration have just appeared: R. H. Williams, The Potential for Electricity Generation as a Byproduct of Industrial Steam Production in New Jersey, report to the NJ Cabinet Energy Committee, June 21, 1976, Center for Environmental Studies, Princeton University; and S. E.

Nydick et al., A Study of Inplant Electric Power Generation in the Chemical, Petroleum Refining, and Paper and Pulp Industries, Thermo Electron Corp. report to FEA, PB 255 658 executive summary) May 1976, and PB 255 659, National Technical Information Service (Springfield, Va). Prof. Williams has kindly called my attention to an informative prospectus for a Weyerhaeuser cogeneration system, available from K W. Rinard, Eugene Water & Electric Board, Eugene, Oreg. It appears that cogeneration could be so attractive as to compete economically with solar heat for both space (with heat pumps) and process, on certain assumptions about allocation of costs between the dual outputs. It would, however, rely on depletable fuels and thus be transitional only [1]. As the use of electricity was gradually trimmed back to appropriate end uses, cogeneration would become less attractive as a source of electricity relative to installed hydroelectric capacity, and as a source of heat relative to solar process heat, materials recycling, or process redesign (note a, page 40).

42. K. Bammert, and G. Groschup. Status Report on Closed-Cycle Power Plants in the Federal Republic of Germany. ASME paper 78–GT–54 for presentation at the Gas Turbine Conference and Products Show, New Orleans, March 21–5, 1976. I am grateful to Prof. Williams for calling this useful paper to my attention.

43. A. E. Haseler. Personal communication. 1976.

44. Project Independence Blueprint. Solar Task Force Report, FEA. (4118–00012, USGPO). November 1974.

45. Good data should emerge from the 22 projects summarized at page III–D–35, Vol. III, Recommendations for a Synthetic Fuels Commercialization Program, Synfuels Interagency Task Force report to President's Energy Resources Council. November 1975.

46. A. D. Poole, and R. H. Williams, Flower Power: Prospects for photosynthetic energy, Bulletin of the Atomic Scientist 32. (5): 48–58, 1976; and M. J. Antal, Jr., ibid., p. 59–62; J. Marshall et al., E–X–25, Forestry Service, Environment Canada, February 1975; Forest Service, USDA, The Feasibility of Utilizing Forest Residues for Energy and Chemicals, NSF/RA–760013, March 1976; C. G. Golueke and P. H. McGauhey, Ann. Rev. Energy 1:257–77, 1976; K. Sarkanen, Science 191:773–6, 1976 and adjacent papers; D. Hayes, Energy: The Case for Conservation, Paper 4, Worldwatch Institute, Washington, D.C., 1976.

47. E. P. Gyftopoulos, et al., Potential Fuel Effectiveness in Industry, Ballinger, Cambridge, Mass., for The Energy Policy Project, 1974; J. A. Day et al., Industrial Process Heat from Solar Energy, UCRL–76390, May 1975; and a large international literature. Solar crop-drying seems ready for immediate large-scale use.

48. A. B. Meinel, in Briefings Before the Task Force on Energy, Subcommittee on Science, Research, and Development, Committee on Science and Astronautics, USHR, Serial U (92d Congress), USGPO, 1972; and in Solar Energy for the Terrestrial Generation of Electricity, hearing before the Subcommittee on Energy, same Committee, 12 (93d Congress), USGPO, 1973. The α/ϵ of about 50 which Meinel mentions, with an apparent lifetime of order 40 years on the basis of accelerated-lifetime tests, has since been bettered in proprietary work. I understand that wet chemical deposition at much lower cost can yield films with α/ϵ of at least 30, but the lifetime is not yet known.

49. H. C. Fischer, The Annual Cycle Energy System. Energy Division, Oak Ridge National Laboratory. 1975. An illustrated but less detailed account of the ACES system, which looks useful for warm climates, appears in Professional Engineer Magazine, June 1976.

50. T. V. Esbensen, and V. Korsgaard. The Zero Energy House. International CIB Symposium (reference 1, note 15), also T. V. Esbensen, personal communication, 1976.

51. Proceedings of the Passive Solar Heating and Cooling Conference and Workshop. Albuquerque, N. Mex. May 18–20, 1976. National Technical Information Service, Springfield, Va., 1976.

52. Calmac Corp., Box 710, Englewood, N.J. 07631; Thomason Solar Homes, Inc., 6802 Walker Mill Rd. SE, Washington, D.C. 20027; W. A. Shurcliff, Active-Type Solar Heating Systems for Houses: a Technology in Ferment, Bulletin of the Atomic Scientist 32 (2):30–40 1976, which includes much good advice and the latest fusible-salts reference.

53. J. M. Weingart, Solar Energy Conversion and the Federal Republic of Germany—Some Systems Considerations. Draft WP–75–158. IIASA, Laxenburg, Austria. December 1975. IIASA studies of solar heating and cooling costs (capital and life-cycle) and of available hardware are in progress. See also S. W. Herman and J. S. Cannon, Energy Futures: Industry and the New Technologies, INFORM 25 Broad St., New York City. 1976.

54. H. van Bremen, and J. M. van Heel. Solar Energy in Local Authority One-Family Houses in Holland. International CIB Symposium (reference 1, note 15). Also H. van Bremen, personal communication, 1976. Interesting comparative data are available for a different climate from the SAGE (solar assisted gas energy) project of the Jet Propulsion Laboratory, Pasadena, and Southern California Gas Co. The field data from a 32-apartment-unit complex will become available late this year from SAGE Project Director, Southern California Gas Co., P.O. Box 3249 Terminal Annex, Los Angeles, Calif.

55. A. D. Little, An Impact Assessment of ASHRAE Standard 90-75, report C–78309 to FEA. December 1975. Summarized in FEA's f. Conservation Paper 43A.

56. D. P. Kamat, et al. Regulatory and Tax Alternatives and the Financing of Electricity Supply. Research Report 7, NSF–RA–N–75–123, Center for Energy Studies, University of Texas, Austin, September 1975. p. 29.

57. Efficient Use of Energy. American Institute of Physics Conference Proceedings 25. American Institute of Physics, New York City. 1975. Gyftopoulos, op cit. [46] and Ross and Williams, op. cit. [15]

58. L. D. Chapman, et al. Electricity Demand: Project Independence and the Clean Air Act. FPC Task Force Report. Oak Ridge National Laboratory, Oak Ridge, Tenn. November 1975. von Hippel and Williams show [32] that the 1975 price of residential electricity would have to more than quadruple to get back to the constant-dollar level of 1940.

59. S. Novick, The Electric Power Industry. Environment 17 (8) p. 7–13, 32–9, November 1975.

60. E. Kahn et al., Investment Planning in the Energy Sector, LBL–4479, Lawrence Berkeley Laboratory, March 1, 1976.

61. This result has been derived both by IIASA and by Dr. Kees Daey Ouwens (Rijks-universiteit Utrecht). I consider both calculations more detailed and persuasive than those of a recent Institute for Energy Analysis study, and hope the discrepancies will be publicly reconciled.

62. I expect this result will appear in the Stanford Research Institute's important study (reference 1, note 30) A Preliminary Social and Environmental Assessment of the ERDA Solar Energy Program 1975–2020, if and when ERDA publishes it (I understand a draft was submitted to ERDA in July 1976).

63. This assumption is stated in terms in ERDA–48 (1975). See the Office of Technology Assessment critique (summarized in Science, 190:535–7, 1975) and the author's critique for the President's Council on Environmental Quality (CEQ hearings, Washington, D.C. Sept. 3, 1975; similar hearings on ERDA–76–1 were held in December 1976).

64. R. A. Falk, Rejecting the Faustian Bargain. The Nation, p. 301–5, March 13, 1976.

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73. A. E. Haseler tells me (1976) that flexible, insulated heat mains for distributing hot water to low-density residential areas can now be delivered on cable drums for rapid installation at very low cost, making district heating economically attractive even for dispersed suburbs.

74. I. Hoglund, and B. Johnsson (Royal Institute of Technology, Stockholm), in their paper at the International CIB Symposium (reference 1, note 15), describe a method they have developed for insulating existing apartment buildings on the outside, so as not to disturb the tenants or make the rooms smaller.

75. H. P. Green, The Risk-Benefit Calculus in Saftey Determinations. 43 George Washington Law Review 791–807, March 1975, also response by P. Handler at 808–13; A. B. Lovins, comments in S. M. Barrager et al., The Economic and Social Costs of Coal and Nuclear Electric Generation: A Framework for Assessment and Illustrative Calculations for the Coal and Nuclear Fuel Cycles, Stanford Research Institute MSU–4133 (USGPO, 1976); A. B. Lovins, George Washington Law Rev., August 1977. (In preparation.)

76. L. Mumford, The Transformations of Man, Harper & Row, Publishers, New York City. 1956.

77. P. Diesing. Reason in Society. University of Illinois Press, Urbana. 1962.

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79. R. E. Miles, Jr., Awakening from the American Dream: The Social and Political Limits to Growth. Summarized in Washington Star. May 9, 1976.

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85. See the report of the summer 1976 Institute for Man and Science (Rensselaerville, N.Y.) workshop on proliferation issues; the rapporteur was Prof. Richard Gardner (Columbia University Law School).

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94. L. Scheniman, Atomic Policy in France Under the Fourth. Republic. Princeton UniversityPress. 1965. As quoted on p. 44–5 of reference 83.

95. Richard J. Barber Associates, LDC Nuclear Power Prospects 1975–1990. ERDA–52, 1975.

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101. I. C. Bupp, and J. C. Derian. Nuclear Reactor Safety: The Twilight of Probability. December 1975 seminar paper available from Prof. Bupp, Harvard Business School.

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GENERAL ENERGY POLICY—III

(By Laura Nader, et al.)

The Lovins synthesis stimulated a major effort by the University of California to investigate the possibilities of the soft path technologies in that State's future. The excerpted chapter that follows analyzes some of the attitudinal barriers to adopting soft technologies, and describes the results of an informal survey of opinion leaders. The discussion divides the debate into a number of antithetical dimensions which are helpful in describing the context in which decisions are made. The orientation of the investigators is obvious if unstated: their mission is to discover why everyone doesn't immediately realize and accept soft technology, such as windmills, and reject hard technology—particularly nuclear power.

[Excerpt From Distributed Energy Systems in California's Future, University of California—September 1977]

BELIEF, BEHAVIOR AND TECHNOLOGIES AS DRIVING FORCES IN TRANSITIONAL STAGES—THE PEOPLE PROBLEM IN DISPERSED ENERGY FUTURES

(By Laura Nader, Norman Millerton, Joseph Palacia, and Catly Rich)

12.1 INTRODUCTION

Transitions may be painful, they may be viewed as a challenge, or they may happen unnoticed. They may be public, or they may be private. They may necessitate individual change or societal change or both. Whatever may be their characteristics transitions they are an ever present factor in human life, and most of them occur without the aid of any public policy.

One major characteristic of the twentieth century is an increased dependency of individuals and groups on large scale institutions. Over the past 40 years both individual and group self-reliance has dramatically decreased. Wage labor and specialization is the overwhelming pattern. With increased interdependence has come increased government planning, increased reliance on expertise, and an increasingly disassociated society, with different segments operating as strangers to one another. The phenomenon of strangers in the same land is in no area better exemplified than in the various dialects that are used by different professional expert groups in the United States. Explosions become "energetic disassemblies" and in the process the explosions themselves become part of some abstract reality for the expert. Public planning cannot operate successfully without an understanding of the consequences of the above mentioned variables.

As we mentioned, in twentieth century America public planning requires the use of the expert professional. Experts, by virtue of their training, are taught to think in a certain way. They are taught a language; they are trained to be loyal to the goals of the profession, and to solve problems in terms of these goals. For some problems the narrow range of an expert is productive: we need to know how much energy can be saved by means of certain technical fixes. For other problems narrowness is not only malproductive, but it produces a view of the world that is not adaptive in times of scarcity; as an agro-industrialist of northern California recently remarked to a reporter who asked him about rainfall: "We don't worry about rain; we irrigate here."

The National Academy of Science has in the past few years carried out several massive projects in areas thought to be crucial to the maintenance of world stability: food, climate, energy and to a lesser extent their interdependence. In all of these studies it became clear that we need to include the expert as a part of any national problem we address.

We need to understand the experts' professional training and perspective on the world, the structure of their work places, and the unexpressed values by which they judge and select their goals. The problems of our world today have a seamless quality about them that does not recognize the narrow confines of expertise or of professional managers. Disciplines are accustomed to relatively closed systems of a manageable number of components. The energy question, like the question of poverty or health, requires that we deal with a network of dynamically related variables; it is not another quest for the moon. Public planners must understand the nature of the work force they hire to tackle national problems.

Energy is a social, not a technological issue. A basic flaw in all energy discussions is that the cultural and social context tends to be left implicit. Yet the major choices in energy paths are being made in the context of different and often conflicting social and cultural systems. These different ideologies or belief systems are linked with what experts have termed "the energy problem." For example, one set of beliefs would see the energy problem as one of developing new supplies to meet the expanding energy needs; another might see the problem as one of reducing appetites, and yet another belief system might reflect the energy problem as a choice between hard or centralized systems and decentralized systems that were either hard or soft. The differing ideologies are associated not only with different expert advice, but also with differing organizations of expert knowledge. There is a need to discuss the myths implicit in assumptions about progress, quality of life, and energy use, for even relatively sophisticated scientists (see Cook, 1976) discuss progress as if it were unilineal in development.

Belief systems are also linked with types of technologies, and there are also a number of hypotheses in the literature which link energy forms with particular social and political effects. For example, hard technologists tend to be optimistic as to what hard technologies can accomplish and pessimistic with regard to soft technologies such as solar. Soft technologists might share a belief that soft, decentralized technologies will be associated with democratic principles, while the hard and centralized technologies would encourage further development of the already dominant military trends in the United States. Lovins admits that both paths, hard and soft, will raise difficult social problems although of very different kinds. The problems of hard technologies are visible today—environmental pollution and increasing militarism. The problems of making a transition from an earlier period toward the hard path are part of our history. Our research addresses itself to a discussion of the most relevant social and cultural dimensions relevant to a transition away from hard technologies towards dispersed, soft, increased self-reliance, if that transition is instigated by government.

When public planning enters the scene, particularly since public planning is often accompanied by large public monies, there develops the belief that changes only happen if they are planned by the government. Experience shows, however, that private planning, whether conscious or unconscious, can and has had a tremendous impact on our society. The automobile was a private invention, produced by private industry, a product which revolutionized our way of life and changed the whole fabric of our society, from family relations to land use. And there are other private patterns—those which result from thousands of individual decisions which coalesce; even though there may not be any meeting or conscious planning, a direction is taken. The decision to have fewer children is a private plan which has also and will bring dramatic changes in the economy of this country, from employment patterns to mental health patterns. Public planning runs into difficulties when it does not recognize parallel change in the private sphere. With these general observations in mind we can now report on our progress in relation to research on the California case.

During the summer of 1977 we began to explore the role of belief systems and their accompanying behavior patterns and technology systems as driving forces in relation to a transition from hard to soft energy paths over the next 25–50 years in California (Lovins 1977). An examination of the conscious and unconscious patterns of transition illustrates how technologies and beliefs and the organizations with which they work, act as constraining and/or incentive forces. We looked at barriers and incentives to conscious and unconscious transitions in the public arena, and in the interactive spheres between the public and private domains. We did not interview people who would be impacted (the general public), or who had no direct role in relation to public planning. Our methodological strategies included telephone and face-to-face interviews with over 50 people (see appendix), people with different involvements in the energy question in California. In addition, we explored some of the out-of-state happenings in New York, Michigan, Wisconsin, and Nebraska, and sampled a number of energy concerned bureaucrats outside of California. Our approach was qualitative, with no intention of using survey research techniques. We interviewed with intent to sharpen our understanding of what the relevant variables should be for any analysis of the role of leaders in transition.

During the past 6–7 weeks we focused our attention on learning about two transitional mechanisms, one which was initiated by a California state agency, and the other which is being initiated by actively concerned citizens. The first mechanism was the California Residential Building Code which was mandated by the California Energy Commission to come into effect March, 1978. The second mechanism, and one which has some earlier history of discussion in California and of practice in countries like Denmark, was the use that could be made of dispersed electric generators as connected to the electric grid. In gathering our information it became clear that although the mechanisms were different they had several dimensions in common, and the following discussion will focus on the dimensions that emerged as central to our understanding of transition in reference to the California Residential Building Code and the exploration of the potential of dispersed electric generators. In particular, we would like to focus upon these dimensions for the benefit of technical persons and bureaucrats who may be only too aware of such dimensions, but as yet unable to raise them to the status of crucial variables.

12.2 SOME DIMENSIONS OF THE "PEOPLE PROBLEM"

Those of us who become part of the action force in promoting adaptive behavior in times of scarcity and/or change to new resources need to become more aware of the roles we are playing, and we need to notice these and other variables as they operate to influence our actions. Here we list some dimensions for purposes of beginning to develop a checklist of concerns for people working on transitions to soft paths. Because these dimensions so often appear in binary opposition it appears that we are dealing with parts of two contrasting paradigms, each adaptive under different conditions. We have chosen to isolate these few dimensions for discussion because in listening to people argue, or in listening to people talk past one another, or in hearing cries of impotent agony these often overlapping aspects were most salient:

(*a*) Institutional constraints vs. individual freedom.
(*b*) Credible vs. non-credible.
(*c*) Tangible vs. abstract.
(*d*) Restricted vs. global time perspective.
(*e*) Specialist vs. generalist.
(*f*) Voluntary vs. involuntary.
(*g*) Progress vs. decline or status quo.

12.2.1 Institutional Constraints vs. Individual Freedom

No matter where we interviewed this summer we ran into direct or indirect commentary on constraints that are organizational in nature. They were perhaps best summarized in the comments of one activist concerned citizen. She reflects upon the lack of freedom of operation among wage workers, particularly those who work in large scale institutions, when she notes: "I don't work for anybody, so I can say what I please." She was commenting upon the slowing effect of bureaucratic procedures and the absence of any sense of urgency when she impatiently requested, "Don't talk to me about 1981 or 1982, I want it now . . ." Her comment on the division of labor in this country which separates those who think about a problem from those who work the problem was "Until you get into the field, you don't know anything." There are important messages here.

A telephone interview with an official of a government foundation in Washington requesting information on the role of agriculture in the solar program received the following response: "Solar energy is not associated with agriculture because solar energy is now associated with other categories at this Foundation . . . Ten years ago it would have been possible to associate solar energy with agriculture, but now if we used solar in connection with agriculture it would confuse the categories associated with solar." Besides, he said, "Trying to change this pattern and associate solar with agriculture would amount to a crusade." Categories in bureaucracies like the NSF or ERDA or any other like organization take on a life of their own that is contradictory to flexible operation in science, and sometimes downright contrary to the goals of science in the public interest. Bureaucrats are there in order to meet the milestones set forth, and if their train is on a successful track as viewed from their expectation of reward they are understandably reluctant to change the direction of the track or the schedules or frequencies of the stops. In short, there seems to be no reward for them to take on any alternative ideas.

In general, bureaucrats are vastly overworked; and without a reward incentive, one can understand their reluctance to undertake any alternative paths. At least by implication, energy bureaucrats are assaulted almost daily by people with ideas that are claimed to be extremely important in the energy business requiring immediate attention. The advancement of a person in a bureaucratic job is defined to exclude the taking of risk. It has been observed that the investment banker makes money only on the basis of taking risks. The bureaucrat does not have this reward structure built in. Soon paperwork and the duplicating machine hides all. When State Energy Commissioners note that the agency has grown from approximately 50 people to 550 people in about two years, and when they note that they feel 'the bureaucrats are taking over,' and when interested citizens can't see what is coming out of a state or federal energy agency that is in direct response to an energy crisis—it may be time to think about new organizations that can function in times of transition and emergency, rather than borrowing a type of organization, for this new era, that has known paralysis diseases.

To return to the freedom of the concerned citizen as contrasted with the constraints of the wage worker (be she/he scientist or other)—as uncomfortable as it may be to scientists, we must raise questions of what organizations do with deviant scientists, with scientists who do not think like the rest. We know what happened to Gofman and Tamplin, but there are others, not so well-known. More important perhaps is to understand that scientists who do stay are being rewarded for thinking in a certain way, and after some years these ways of thinking become God's Truth, assumptions not to be challenged. In the energy field, energy experts tend to think in terms of the way to satisfy the energy demand as projected, by the way, by energy industries. They do not think in terms of non-commercial sources of energy: firewood, cow dung, agricultural wastes, or in broader terms—solar. It may be the time to call a spade a spade, and to call solar derived goodies just that—solar derived fossil fuels, plants, etc. A return to the original source in labeling, as with the solar example, would be part of a process necessary to educating people in the basics. Then, the agro-executive would know that he should be concerned with rain, because irrigation derives from rain.

12.2.2 Credible vs noncredible

Public acceptance is related to a number of variables such as price, status, convenience, and in a more general sense credibility. Credibility is crucial to implementing any policy requiring public cooperation (Hoos 1976). Recent polls have shown that citizen trust in what the government is saying about energy is at a low point. One study reported in Science (Murray et al. 1974) noted that only about 8 percent of the people surveyed believed what the government was saying about energy.

Credibility is diminished by a number of factors: (1) the gap between what the government says and what government does, particularly in areas observable to the average person (e.g. by visiting government buildings); (2) diversity of opinion among experts, which is seen by the public as lack of agreement among experts; (3) scientific overconfidence ("Often wrong but seldom in doubt," which translates as an oversell of science); (4) industry-invented shortages with the motive of increasing profit; (5) self-serving practice in public and private administration of invoking "expert" advice; (6) single angle analysis rather than a holistic approach, for example, only technical aspects or nuclear or solar energy rather than the socio-cultural context within which they will operate; (7) extension of the role of expert, for example, nuclear scientists talking about the "necessity of nuclear power," which is not a technological question, but rather one requiring social and economic expertise, or creating a technology without consideration of the kinds of expertise needed—"the people problem"; (8) ascribing of credibility to experts who may or may not merit it. An example from the Bay area: people are saving more water than anybody dreamed possible, and using more gasoline than ever before.

Questions of price, status, and convenience are more particular. Expensive or convenient for whom, when? In addition to credibility, then, there is the need to know something about the potential cooperating population: the present variety of lifestyles and energy consumption patterns in the U.S. is wide. We have come to accept a homogeneous perspective of American society, based on the lifestyle ideals of the upwardly mobile middle class. The opportunity of personal choice in lifestyle and the potential for a heterogeneous society must be understood and utilized in our projections and plans for the future.

We can learn from past mistakes. The long-term inadequacy of educational, welfare and urban planning was based on erroneous assumptions regarding family composition. The "ideal" family was thought to be a father who works and supports the others, a mother who keeps house and cares for the children, and children who are totally dependent on their parents for all their needs. However, this description held true for only about half the families in the U.S. Ethnographies on American communities show an amazing diversity of attitudes toward wealth and well-being and of mechanisms for gaining and displaying status (Vidich and Bensman, 1958). When there is diversity in the population the solutions or the pathways might do well to be diverse as well—different paths appealing to different people. Some people are born conservationists, others prefer a solar technical fix, some like the idea of dispersed electricity generation, and some wouldn't want to be bothered. Whatever paths we pursue there needs to be visibility and role modeling.

12.2.3 Tangible vs Abstract

It appears that the public is convinced that there is a water shortage by their first-hand experience of a lack of rainfall and because they believe the evidence shown them that water reservoirs are extremely low. Oil, on the other hand, seems to be in superabundant supply. There is no shortage of gasoline. In fact, the newspapers carry statements that there is a glut of oil. Government on the federal and state level is free to admit the presence of this oil glut, remarking that it is very unfortunate because a genuine shortage of oil is soon to follow. A commonly held opinion within government and among experts is that the public will only respond to a visible crisis. One way they argue to make it visible and to clear up the ambiguity is to raise prices. The public may fall into line if the price goes up high enough, but such behavior will in no way compare to the cooperation that stems from a credible story on water. There is an important point being made, however, and in conjunction with the credibility problem we might look at the question of tangible/abstract in terms of role modeling.

Large organizations in this state are building new buildings and are continuing to face increasing fuel bills for space heating, hot water, air conditioning, refrigeration, etc. What are these leading institutions doing that would contribute to their becoming more energy efficient? Only a few educational institutions, such as San Jose State University, are actively engaged with their own plants.

At a Bay area university there is a large new building being built. No solar space heating or hot water is planned for this building. Apparently those controlling the investment capital have made a decision that any methods for heating or cooling buildings should pay for themselves within 5 years. If this 5 year pay-off period cannot be met, the old established methods for heating, cooling, and hot water will be used.

The public may well ask, if there is indeed need for energy efficiency, why aren't these leading institutions in the state converting at least one major building to solar space heating, paying special attention to using a combination of passive and active system design? With the university systems there is a reservoir of expertise unmatched in other institutions. Within state government there is money laid aside for retrofit—again few visible products.

Perhaps the most visible example of abstractness of goals is in the state energy commission building. It is a source of embarrassment to the commissioners and their staff at the state of California Energy, Resources and Development Commission that the new building housing their activities at 1111 Howe Avenue in Sacramento has no solar facilities and is a poor example of energy conservation. In short, from an energy use standpoint, this complex of offices is wasteful, poorly conceived, and out-of-step with the purposes of the commission. As far as we know there is no detailed study of their own plight in this regard.

Moral of the story: "do as I say" must be accompanied by a model worthy of "doing as I do." Carter's plan to solarize the White House would be an example of role modeling.

12.2.4 Restricted vs Global Time Perspective

In discussing energy questions time appears in many forms. A restricted time perspective might describe solar as an intermittent energy source, and thus not dependable. Correspondingly, in a more global long time perspective all nonrenewable sources of energy are disastrously intermittent. In a restricted sense technology has bought us time; we can now cross the country by jet in a matter of hours. In a broader sense, however, technology has not expanded our time, as illustrated by Linder (1970) in "The Harried Leisure Class." For urbanites discussing land productivity 50 years of time is a long time, while many farmers in this country would find saturation of land within a span of 50 years to be an unacceptably short term use of land. Flat plate collectors might not be used on the Stanford University campus because the policy of the University was a 5-year or less pay off time.

Time also enters in relation to the amount of time it takes to get things moving. The public might well ask why the government is not doing things now (not 1980), while the government assumes that because the people do not respond to an announcement of an energy crisis they will be slow to respond to change, e.g. take a long time.

Time is also being used as incentive; in Princeton, there are feedback studies being done which inform people how much energy was used in the last day. It is believed by industry to take a long time to make changes in production; the same people believe that the American people only respond to sudden change, that is, change that does not occur over a long period of time.

It is important to fit the time perspective to the problem. Restricted time perspectives are not what we need for environmental protection, nor for encouraging conservation in building. On the other hand, short term feed-back in savings for households might appeal to the "piggy bank" that is in us all.

12.2.5 Specialist vs Generalist

In our introduction we have already alluded to the problems of expertise: inability to see the piece in the whole, loyalty to professional goals rather than wider social goals, insecurity generated by the fact that most experts are wage workers, insulation generated by the fact that expert language protects the expert from outside criticism (not everyone knows what an energetic disassembly is), and increasing inability to entertain simple solutions or to deal with mundane problems (how many architects in this country know anything about energy efficiency; how many experts on decommissioning of nuclear plants are there; how many drinking water experts are there?). It is because of such observations that Lovins and others have urged that the non-expert be brought into the dialogue over energy.

It must also be underlined that by the very form of initiation or induction all professionals are ideologically bound. Professional expert ideologies are sometimes referred to as mind-sets. Such mind-sets often indicate what one tends to be optimistic or pessimistic about. Nuclear experts are generally pessimistic about solar, as are other professionals who do not find solar intellectually challenging. Retrofit, a nice mundane concept, did not have much potential almost, all of our energy expert officials agreed. As we moved into the John Q. Public level there was genuine interest in retrofit because it was something that people of low skill could learn to do.

A final comment. Professional training teaches one how to stay in business. There is a history in the United States of incompetent professionalism (whether it be in producing cars, curing drug addicts, or practicing law or medicine) breeding an increased need for that profession's services. Again, we need to find ways to encourage professional public service while at the same time restructuring professional fears for self-preservation.

12.2.6 Voluntary vs Involuntary

There are a number of concepts which are related to the voluntary vs. involuntary dimension. The contrast in discussing the building code was drawn between certainty and responsibility on the one hand and freedom and creativity on the other. The further down the totem pole we got the more certainty people wanted, while the further up the more freedom the architects and materials people wanted. It would be interesting to know if this cut would hold with a wider sample.

In discussing this same building code, another set of terms was frequently used: prescriptive and performance. The prescriptive code is specific on the amount of insulation, climate control, orientation, window spacing, lighting, etc. The performance code (which has not yet been written) provides wider parameters within which a certain level of energy is to be used. While architects prefer performance, one building inspector had the following to say: 'Specification is understandable; performance is not understandable.' He also said there would be full compliance with a prescriptive code on the part of builders and inspectors, 'because they can relate to the measure. Performance is that never-never land of architects and engineers.' This inspector is involved in the training of building inspectors. Actually, we were told that the code would permit a person to build within the total energy budget as an alternative to building according to the prescribed standards, so it is doubly interesting that the code was stigmatized as prescriptive.

There is a further note to be made on the voluntary dimension. While in many ways one of the characteristics noted by outsiders about Americans is their cooperativeness and ability to respond voluntarily most of the officials and professionals we spoke to were convinced that change would have to be mandated, that we could not expect voluntary change. All had ways of "explaining" Californian behavior on the drought in the face of price increase with decreased consumption of water. We have a staff at Stanford looking into "social marketing" of conservation measures—their assumption being that Americans can only be educated or seduced into energy efficiency. Again there are untested assumptions, and we need to key into the conditions that are conducive to voluntary change, or change by incentive. When do punitive measures (price increase which is always favored by economists), versus reward measures (tax incentives which are often proposed by citizens) work best? I believe if we examined the literature in psychology that reward systems would come out ahead in motivating large U.S. population groups.

12.2.7 Progress vs decline or status quo

Much of the hostility towards soft paths stems from a self-serving view of progress which does not fit with a global evolutionary perspective, but which is part of a restricted time perspective. For the most part, in this view, technology is used as a measure of progress, and it is the presence of technology rather than its use or consequence that provides the measure. Progress, for example, is said to have eliminated the drudgery of women's work, yet in terms of hours/housework it takes as much time today as at the turn of the century. More interestingly, however, the cost of progress is swept under the rug by a clever technique invented by economists—externalities or long term costs. Again time perspective is important. Most hard path advocates believe the erroneous thesis presented in Cook (1976) of linear societal evolution in relation to perceived patterns of energy use. It should be remembered that cultural progress is dependent upon factors other than those arising from the use of energy, and that how that energy is used rather than the use of energy per se is related to improved quality of life, or decline in living quality.

With these dimensions roughly in mind we now turn to two contemporary mechanisms for transition: the California Residential Building Code, and the use of dispersed electric generators. When we look at the code and listen to the arguments over prescriptive vs. performance we need to remember that some of those who object to prescription presently abide by prescription. However, the prescriptions builders, for example, abide by originate from their industry and not from an outside source such as the Energy Commission. When we look at the potential use of dispersed electric generators we will recall that institutions have a coherence about them. Changing public utilities relations with consumers will be seen as disruptive to the status quo. More frequently than we might like to admit in this country, major institutions operate from fear and cloak their fear in symbolic representations such as that embodied in the concept of progress.

[Editor's Note: Section 12.3 on the California Residential Building Code has been omitted.]

12.4 RESTRAINTS ON DISPERSED ELECTRIC GENERATION: INSTITUTIONAL AND IDEOLOGICAL BARRIERS BOTH PUBLIC AND PRIVATE

Information on this question has been collected from a variety of states: Wisconsin, Michigan, New York, and California. What follows is the essence of the California situation as learned from talking to representatives of public utilities, citizen action groups, and a variety of other people listed in Appendix XII–2.

Our questions to the Public Utilities were straightforward. What presently is the attitude of California electric utilities toward small, privately owned installations that would use electric power from the utility and be capable of the delivery of power to the utility, thereby using the utility grid as supply and storage for electric power? Does the public utility welcome small generator-users connected in parallel to their system? Both the Pacific Gas and Electric Company and the Southern California Edison Company, for example, state publicly that they not only welcome the connection of small privately owned electric generators, but that they are soliciting this type of connection. One representative of the Southern California Edison Company maintains that presently he has contracts being written for about 584 million watts of power from small electric generators, which he maintains will be in operation about the first of the year.

There are, however, some problems: the price the utilities are willing to pay for dispersed power, and their willingness to relinquish control over the source of power that they sell. Southern Cal Edison will pay 11 mils (one mil equals 1/1000 dollar) per kilowatt-hour peak, 7 mils for mid peak, and about 3 mils for minimum peak power. (These rates correspond to about 33 mils, 22 mils, and 10 mils in charges respectively.)

These purchase rates are arrived at by Edison by averaging the costs of all the types of existing facilities within Southern California Edison. They have little or nothing to do with the cost of new generating capacity to be constructed for ownership by the Southern Cal Edison Company. Needless to say, the new generating capacity will be coming in at prices greater than $1,000 of investment for each busbar kilowatt (that is, at the electric power plant); and by Southern Cal Edison's own direct admission the price for new generator capacity will rise soon to $1,500 per installed kilowatt. Translated into consumer costs, the cost of electric power would be greater than $0.03 per kilowatt-hour rising to $0.045 per kilowatt-hour. In fact, if the fuel costs rise after the generators are built, the cost per kilowatt hour could continue on an inflationary spiral soon reaching present prices typical of the Eastern Seaboard of the United States—5 cents, 6 cents, and up to 10 cents per kilowatt-hour. Detroit Edison in Michigan charges 3.85 cents/kilowatt-hour. They will pay 11 cents/kilowatt-hour for power but charge $6.50/month for this service as contrasted to $2.50/m for regular service. New York City presently charges 10 cents per kilowatt-hour for peak power, and has been forced by a New York State Supreme Court decision to pay 25 mils per kilowatt hour for power from small generators such as windmills. P. G. & E. charges about 33 mils per kilowatt-hour and is offering 14 mils per kilowatt hour peak for power from small generators. As of mid-August, P. G. &. E. maintains they have not had any takers of their offer.

It seems safe to assume that if a utility would pay more for power from small generators, there would be more interest from people in contructing generating facilitites with their own capital. To be consistent with their own self-interest, the Public Utility must own the means of generating the power. This is because of the attitude expressed by the Public Utility's Commission in California, and incidently, practically everywhere else in the world.

Presently, the Public Utility is allowed to charge for electric power in terms of their capital investment. It does not matter whether the capital investment is actually functioning or what type of fuel the particular generating system uses. The rules of the game are: more capital investment by the utility yields proportionately higher rates to be paid by the consumer. In fact, one interpretation of incentive has it that a Public Utility can therefore make money on facilities that do not work. A Public Utility cannot charge higher rates unless they put in more investment, owning the means of generation is the major investment required. Under these rules established by precedent and present attitude, the Public Utility cannot serve their own self interest by paying more than their average rates for dispersed electric power owned by other than the Utility. It is probable that federal legislation will supersede state legislation on this point in the near future. As a reference point, federal power costs less than 3 mils/kilowatt-hour.

There has been citizen activity in this area, in and out of California. In Wisconsin, Wind Works has been active with the energetic participation of Congressman Reuss. In New York City similar interests in wind power have sought a court decision that would favor more pay for power from small generating units. In California, a number of organizations, including TURN (Toward Utility Rate Normalization), located in San Francisco, have actively sought to change the rate that Public Utilities will be required to pay from dispersed generators. They would like the rate to be tied to the cost of new generating capacity rather than the system average rates. This would mean that a real incentive would be given to the small private owner for installing small generators.

As more and more small generators come into operation, the role of the Public Utility would alter from primarily that of electric power generation to primarily that of electric power distribution. Some advocates of dispersed electric power generators feel that the Utility should pay one-half the amount for dispersed power that it can sell power for. One suggestion is that this pattern of payment should follow the Agricultural Share Croppers-Land Owners relationship, where one-half of the crop is given to the land owner, and the other half is kept by the share cropper (private communication by O. J. M. Smith, 1977).

A number of people are alert to the problem of self interest in the electric utilities. While the utilities cannot be expected to want to put themselves out of business, or to reduce their economic return to their investors, it is possible to alter the relation between consumer and producer so that the goals of the utilities and the wider good mesh in a more productive and stable relationship. As it appears now however, the Public Utility is interested in preserving itself as it is. Accordingly, small scale windmill electric power generators are to be tolerated until the number of these generators become so large that their presence would offset generating capability by the Utility. If the Utility felt that its rate base were threatened by the dispersed generators, then it is likely they would try to become the owners of the new generating facilities as happened in Denmark. It is possible that the Public Utility would cooperate and even stimulate dispersed electric generators if it were shown to be in their self interest to do so. Presently electric research institutes like EPRI in Stanford have little interest; they do not have any studies concerned with small scale dispersed generation of electric power whether from total energy concepts within existing buildings or from windmill generators in rural settings. On the other hand research on windmill electric generators is being conducted at Livermore and a number of other national labs and government supported labs.

It would seem then, that by a shift in attitude on the part of the Public Utilities Commission in California, a new relation could be established where many small owners would invest their capital in the erection of small electric generators. For example, based upon the previous installation of windmills there are at least 200,000 rural sites in California (Smith, 1977 private communication) where wind is sufficiently strong and reliable so that each site could carry a new windmill driving an electric generator. Each one of these sites is already supplied with 10 kilowatt service; that is the wires, meter, switch, circuit breaker, etc. are already installed. It has been pointed out (Smith, 1977 private communication) that a pair of wires could be run from each existing electric service to a windmill generator thus minimizing the cost for the new hook-up. Clearly this would provide 2 billion watts of new electric generating capacity without requiring much investment from the existing Public Utility Network. This amount of new electric generating facility could make it unnecessary to build any type of generating central plant in California for some period of years. No nuclear, no new fossil fuel, no new hydroelectric or geothermal plants would be needed.

One interview with a State Energy Commissioner reveals both attitudinal and institutional constraints:

INTERVIEWER. If you can identify 200,000 rural sites, multiply by 10, (kilowatts each) and you have a significant amount of electricity.

COMMISSIONER. It sounds like someone should get into the business.

INTERVIEWER. How about the Energy Commission?

COMMISSIONER. We're not in the manufacturing business.

INTERVIEWER. But the Commission is a stimulator.

COMMISSIONER. We might assist with a demonstrator.

* * * * * * *

INTERVIEWER: * * * The precedent is there so that a bunch of dispersed generators can feed the grid.

Commissioner: As I said, from what you told me, it sounds reasonable. We would in a small way help, but *we are involved in more macroscopic projects.* (italic ours).

This and other interviews silhouette the problem of institutional constraints. In experimental science facilities Russia has demonstrated the pattern that builders of equipment shall be distinct and separate from the scientific users of the equipment. For example, most of their new accelerators for physics research were designed and built by a building group to a set of specifications. The building group was not allowed, let alone encouraged, to have contact with the using group. The building group then delivered the finished machine to the people that were to use it. To date, this has resulted in a level of mediocrity and time wasting effort. It would seem to be axiomatic that the people most interested in the success of a project should be involved in the earliest development of the project. There must be a continuity between initiator, builder and user. Oftentimes innovative projects in the United States have involved a very few individuals in this continuity relationship. Projects have been spark-plugged and brought into fruition—forced, if you will—to be successful, simply by the will, skill and guts of, in some cases, one individual. On the other hand, if we look at government entities such as the State Energy Commission or ERDA, we find that the conception and the charter of these organizations leads to grave problems. There is no mission to demonstrate success in a practical sense. There is no continuity or carry over from the research and development to the actual operation and maintenance of the devices. They are only able to study and illustrate by demonstration projects—the delivery and maintenance of practical service is left to others.

In the view of some, dispersed generators are not macroscopic in scope. An approximate projection in California would be that the population will double within the next 37 years. By letting people make a dollar from conservation and make use of their own labor and private capital, it should be possible to supply more than adequate electric power to twice the population of California with the same installed capacity we have in California presently. This is based upon the observation (Smith, private communication 1977) that California has twice as much installed generation capacity as we are presently using. Part of this extra capacity is necessary as a safety feature where unforeseen problems, shutdowns due to the weather, etc. allow the system to keep on functioning. The addition of 2 billion watts of new capacity dispersed over the state would add a highly reliable component to the existing electric power generating network.

It may be that people in ordinary walks of life are better able to realize the potential of the sun and its offspring wind than are experts in the energy business and officers in public and private institutions. During the 1948 power shortage in California there was an attempt to utilize the electric generating potential of induction motors normally used to pump water. Ralph Parks, an agricultural engineer in extension services at Davis, went around the state demonstrating this on site to farmers in rural California in the spring of 1948. His innovative attempts were cut short because the power shortage in California was over before many people had tried to implement his suggestion.

We have spoken about the constraints on professionals and on government agencies, but the picture was not much different when we turned to an independent, private institution like Stanford University. The question was asked of a Stanford official: "Why aren't windmill generators or cogeneration facilities being established on the Stanford campus, or on other lands under control of Stanford University?" The response was that selling electric power from Stanford University to any Public Utility places Stanford in the position of being regulated by the Public Utilities Commission in California. It would seem unacceptable that the Public Utilities Commission should have regulatory control over an institution like Stanford University. When this question was raised with the legal staff of the Public Utilities Commission, the response was that the required regulation did not have the character implied. A parallel was drawn between an institution owning a source of water and their selling this water to the public.

The state of California requires regulation of water sources that are sold to the public. But, below a certain capacity for water delivery, this regulation does not extend into the affairs of the private seller of water. Quality of water is monitored, but the internal affairs of the institution are otherwise left alone. The PUC legal staff has judged that any institution such as Stanford University, the University of California, etc. could get a simple letter approved delimiting the regulation of their affairs by the Public Utilities Commission. Such a letter of application could be routinely approved. The question is left hanging, why aren't our institutions of higher learning using their own investment capital to demonstrate to the public that conservation is both prudent and a way to make money for the institution? And why are these institutions not demonstrating leadership? It may be that we need a new division of labor in organizations whereby piecework is replaced by the need for whole job responsibility, and we need to do this in the name of efficiency. We have come full circle.

12.5 FUTURE RESEARCH

In studying the residential building code we have looked at the institutional barriers toward transition toward energy efficient use when introduced through legislation. Directions for further study of residences should include:

(*a*) A study of the City of Davis where a residential building code similar to that of the Commission's has already been operational, with particular attention to the method of appeal and to the hypothesis of a variety of people interviewed that legislative mandates should best be implemented on a decentralized plan.

(*b*) Attention to ways of circumventing legislation.

(*c*) Attention to special interest groups such as the National Association of Concrete Masonry, and consumer reactions: house owners, house renters, state house financing agencies, low income groups.

(*d*) Attention to building regulations and mandated change in general.

It would be worthwhile to continue work on the non-technical and technical problems of realizing large numbers of small electric power generators in rural California driven by windmills, Stirling solar engines, cogeneration, or total generation sources, etc. The present work can be profitably extended along several lines expressed therein focusing on three facets of such technology: cost estimation, vulnerability, and the value of reliability.

In sum, we are saying that building codes and dispersed generation are useful pivot points for raising questions about transitional tactics. So as to generalize any findings beyond these two particular mechanisms we would suggest expanding the idea of dimensions as a checklist for change inducing personnel. The dimensions explored but superficially in this working paper are crucial to how and if things happen.

In addition, it became clear from our interviews this summer that we need to plan for education. A variety of people commented on what the other guy needs to know but doesn't. A retrofit specialist wants to educate architects and engineers in heating and conservation efficiency; another group thought that we needed to educate builders, another the building inspectors. Another University group was working on educating consumers by "social marketing tactics" and by various kinds of "feedback studies." Do-it-yourself retrofit would be a useful educational technique whatever the cost effectiveness, and if in the process we provide jobs for the low skilled, again the educational effort would be important to measure beyond cost effectiveness. Energy extensions have been talked about. The concept must, if our interviewees are correct, reach beyond educating the little people in the value of efficiency or on informing consumers of their rights in efficiency mandates.

APPENDIX XII–2

In carrying out the dispersed electric generator work, we interviewed 70 persons. The following is a breakdown of the groups represented.

	Number interviewed
Stanford University, professor of engineering	1
U.C. Berkeley professors	10
State energy commissioners	3
State energy commission staff	15
State architects' staff	1
Lawyer, consumer organization	4
Engineer, public utility	6
Official, Energy, U.S. Government	1
Official, energy, California government	7
Energy specialist, national laboratory	6
Engineer, State of California water resources	1
Energy scientist, nonprofit institute	2
Energy specialist, U.S. Congressman's staff	1
Education person, national laboratory	1
Engineer, wind-works	1
Newspaper reporter	1
Lawyer, public utilities commission	2
Staff planner, a California county	1
Engineer, agriculture	4
Consumer activist, Windependance	1
Science writer	1
Public information officer, EBMUD	1
Engineer, sales	1
Scientific attaché	1
Scientist, National Resources Council	1
Engineer, U.S. Air Force base	2
University of Rhode Island, professor	1
Statistician, Edison Electric Institute	1
Resident-Owner solar home, Rhode Island	1
Builder, solar home, Rhode Island	1

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THE UTILITY INDUSTRY—I

(By Edward Berlin, et al.)

The present structure of the utility industry is one in which relatively few large private and public utilities, vertically integrated to combine generation, transmission and distribution of electricity, predominate, while numerous small utilities, mostly publicly owned, fill out the system as distributors of bulk-purchased power.

There is a tendency to regard this structure as ordained from above and immutable, so that any changes in future energy generation and use must be accomodated within the basic framework. Such an approach may be needlessly rigid. The next selection, part of a report to the Ford Foundation's Energy Policy Project, advocates a radical change in the markup of the industry, particularly by eliminating the vertical integration of the large utilities and separating the generation, transmission and distribution functions. Many of the arguments have been rendered moot by events that have taken place since the report was issued, but the article is a good exercise in pondering various ways in which the industry could be reorganized.

[Excerpt from Perspective on Power: A Study of the Regulation and Pricing of Electric Power]

RESTRUCTURING THE ELECTRIC POWER INDUSTRY

(By Edward Berlin, Charles J. Cicchetti, and William S. Gillen)

CONCENTRATION AND COMPETITION

The electric power industry has been moving toward concentration over the past several decades. In 1945 there were approximately 4,051 electric utilities in operation in the United States (1,060 of which were privately owned). Today the number is less than 3,500 with perhaps fewer than 300 privately owned systems remaining. For the most part the industry is vertically integrated. That is, a single entity produces (generates), transmits and distributes electricity. In addition, most utilities are interconnected with neighboring utilities.

In view of the existence of vertical integration we question the appropriateness of further concentrations of corporate control (for example, through mergers). Indeed, our legal system requires that horizontal competition be protected and furthered wherever possible. It is particularly important that interutility competition for customer loads be promoted in the electric power industry. The desire to achieve the efficient allocation of resources and to stimulate technological innovation demands no less.[1] The concentration of corporate control is eroding the opportunities that do exist for competition within the industry. While it is true that electric utilities are operating largely as protected monopolies they have competed for wholesale sales, industrial sales, new service areas, and public acceptability ("yardstick" competition).

Wholesale sales—that is, purchases of electricity by a utility for ultimate resale—are common throughout the industry. In view of economy dispatch or shared savings arrangements and the near certainty that any system (as a consequence of an unscheduled outage) will find itself short of capacity, every utility can expect at times to assume the role of purchaser. The overwhelming number of smaller utilities (predominantly publicly owned) rely most heavily on purchased power.

Strong regional and interregional transmission ties, in addition to recent antitrust pronouncements (principally the *Otter Tail* decision), suggest that smaller utilities should be assured a wider choice of wholesale power suppliers. However, as corporate control is merged and as generation and transmission capacity comes under the control of a few dominant utilities, the practical opportunities for wholesale competition are reduced. Indeed, one of the consequences of joint planning is that the major utilities in an area stagger their construction activities. Thus, at any particular time there may be only one utility with excess capacity available for sale to small wholesale customers.

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[1] It is well to keep in mind that regulation is not intended to displace competition. In passing upon the propriety of a bank merger the Supreme Court has noted (*United States* v. *Philadelphia National Bank*, 374 U.S. 321, 321 (1962)):

"... that the forces of competition be allowed to operate within the broad framework of government regulation of the industry. The fact that banking is a highly regulated industry critical to the Nation's welfare makes the play of competition not less important but more so. . . . Subject to narrow qualifications, it is surely the case that competition is our fundamental national economic policy, offering as it does the only alternative to the cartelization or government regimentation of large portions of the economy. . . ."

See also *United States* v. *El Paso Natural Gas*, 376 U.S. 651 (1964).

Accordingly, although the wholesale customer is usually a high load factor customer, which improves the economic position of the seller enabling it to take fuller advantage of any economies of scale, the small utility which desperately requires an incremental supply of purchased power may have very little bargaining leverage. The antitrust laws, which are cumbersome and expensive to enforce by private entities, offer little practical comfort to smaller utilities experiencing an imminent power deficiency.

There should also be aggressive competition for industrial and commercial loads. While the potential for such competition is most obvious in the case of contiguous power suppliers, it is not necessarily limited by geographic location. With rising energy costs and recurring brownouts and voltage reductions, managements of industrial enterprises will consider power supply factors (both price and the quality or dependability of service) as they assess geographical areas for future industrial expansion. Where the distribution systems of two or more utilities are contiguous, the possibility of interface competition is apparent. This is particularly so where their distribution systems extend to the fringe of areas not yet extensively developed (this is the case with respect to the popular "new town" phenomenon).

Finally, we must not ignore the present and perhaps renewed relevance of yardstick competition. As regulatory commissions are inundated with repeated rate increase filings, as environmentalists attack the social consequences of utility operations, and as investors realize the long term realities of the erosion of earnings and escalating capital costs, the potential for comparative analysis becomes even more imperative. However, such analysis is possible only if the industry enjoys diversity in management philosophies and regulatory commissions can assess the performance of many distribution entities operating within the same general geographic area.[2]

The maintenance of effective regulation is another factor which militates strongly against the concentration of ownership. The undue concentration of control could well frustrate both federal and state (but, arguably, not regional) regulation. Under the existing regulatory scheme the FPC's jurisdiction extends only to wholesale sales which only represent a minor portion of total utility earnings. If a single vertically integrated utility dominates a region, the extent of its wholesale transactions (and therefore exposure to FPC regulation) is minimal and perhaps nonexistent. The absence of FPC supervision will have prejudicial consequences at the local level. Generally, state commission staff resources are severely limited. Therefore, in their regulation of retail activities, state commissions rely heavily on the guidance supplied by FPC regulation of wholesale sales. Without such sales, and therefore without FPC guidance, the ability of state commissions to cope with the regulatory problems presented by large vertically integrated utilities will often be overwhelming.

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[2] As Professor Leonard Weiss observed in the AEP-Columbus and Southern proceeding, (Justice Department Exhibit 220, p. 10):

"Finally, regulatory personnel are in constant contact with the utilities within their own state and have much less contact with those in other states. They are likely to be particularly influenced by local experience in setting criteria for 'prudent costs,' 'reasonable return' or 'reasonable rates' when they try to determine what rates are most appropriate within their jurisdictions. If the state regulatory authorities are faced by only one or a few utilities they will have few relevant criteria. It is not easy to determine which costs are unavoidable and which are unnecessary. The existence of a variety of utilities against which decisions for any one can be tested probably makes regulation more effective."

Moreover, if utility operations are multistate in nature, individual state commissions will be confronted with complex cost allocation problems that would serve to frustrate their regulation of even activities which are intrastate in character. It could also impair regulatory supervision of bulk power supply planning and erode the inherent advantages of local management in what essentially is a service industry.

VERTICAL INTEGRATION

The adoption of a regional commission system of regulation would overcome these difficulties to a considerable extent, particularly if the new regulatory entities have the resources required to enable them to analyze in detail the activities of regulated firms. The restructuring of regulation alone, however, would not achieve the advantages of more aggressive interutility competition and of management diversity. A complementary restructuring of industry is required—a restructuring that would end vertical integration by separating generation and transmission from distribution.

Effective regional pooling would offer the benefits of differing management philosophies but it would not resolve the problems of vertical integration. Indeed, they may even be exacerbated through the introduction of horizontal restraints (which may only be implicit) among pool participants. For example, a smaller utility which wants to participate in the ownership of a new, large base-load unit understandably may shy away from interface competition with the project's major owners. It is inescapable that pooling fosters collusion; this is particularly significant when the collaborators are vertically integrated monopolies.

Further, the very existence of the merger possibility may stand as an inhibition to joint planning and coordination. If a small investor owned utility is denied the rate base advantages inherent in joint participation, its financial stability could well be impaired, making it a prime target for takeover. While rate base erosion considerations are of little or no relevance in the case of consumer owned systems, if they are denied access to new efficient units, and made to pay a less attractive rate for purchased power with a corresponding inability to compete for new growth, it is conceivable that acquisition overtures by privately owned suppliers will be difficult to resist, particularly where the local population witnesses discriminatory (as between wholesale and retail customer classes) pricing.

Consistent with the prejudice of our national antitrust policy, vertical integration must be precluded unless the proponents of vertical integration can demonstrate that its benefits outweigh the implicit prejudice. They have not yet even been asked to do so. With lingering visions of the truly local utility, the nation has passively accepted the logic of tying together under a single corporate umbrella production, transmission and distribution activities.

But this merger of separable functions unnecessarily reduces competition and strains both the utilities and society. It is easy enough to understand why the industry would develop along those lines as individual, isolated central station service systems were placed in operation almost a century ago. But today the industry is, for the most part, fully integrated and generation sources are often far removed from load centers. Each utility is under pressure to become a bulk power supplier either as a means of securing access to newer, more efficient generating forms thereby permitting it to compete for loads, or as a demonstration of its ability to keep pace with industry counterparts. As long as utilities are subjected to rate base regulation and compete in the same capital market, this psychological factor cannot be dismissed. Yet the availability of the technical expertise required for the operational management of the new complex units is limited.

Moreover, acceptable sites are not to be found in each and every utility back yard. Nevertheless it is often the case that utilities are required (in some cases legally; in many more because of practical corporate limitations) to locate facilities close to their service areas. In view of the promised advances in extra high voltage transmission any such locational limitations must be questioned.[3] The prognosis for high capacity (superconducting, cryogenic) underground transmission is most encouraging for the decades of the 1980s and 90s. Once a basic national grid is installed (analogous to our interstate highway system) it should be possible to locate bulk power supply facilities almost without regard for their proximity to load centers. The industry will also have a far greater ability to take advantage of regional load diversity, thereby lessening the total national requirements for generating capacity.

If power bulk plants are to be further divorced from load centers—as they most certainly will be if the nation moves in the direction of off-shore nuclear islands—and are to be under the operational management of technical specialists (as many joint projects already are), it is difficult to justify the vertical integration of production and distribution activities.

The siting and operation of mammoth new power plant installations and extra high voltage networks has demanded technical expertise in planning and decision making not previously required, as well as management skills different from those which have been essential to the operation of even the larger distribution systems. Indeed, the continuation of vertical integration would lead to management inefficiency by requiring the retention of technicians whose skills are not needed in the operation of distribution systems. In this respect the merger of production and distribution activities has even less to support it than does the merger of electric and natural gas distribution activities. Yet even those economies are considered by many to be minimal and more than offset by the competitive disadvantages.

The only conceivable justification for vertical integration, therefore, is the need to provide an opportunity for capital expansion in view of the dependence on rate base regulation. This justification is insufficient on several counts. First, if distribution companies do not build future generation and transmission facilities they will not need an ever increasing source of capital finance (a need occasioned by high cost capacity additions). Therefore, there is no need for an expanding rate base. Second, as already pointed out, regulators are not tied to rate base methodologies. Ample economic rewards can be bestowed upon distribution entities regardless of the static, or even diminishing, nature of their capital plants. Third, if rate base expansion is considered important, construction of underground local distribution lines and the installation of equipment to facilitate peak load pricing will afford distribution companies ample opportunities to increase their capital investments. At the distribution level it generally is accepted that economies of scale are not dependent on the total utility load once it achieves a fairly modest size.

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[3] See *Underground Power Transmission*, a study prepared by Arthur D. Little, Inc. for the Electric Research Council (October 1971), and *FCST Energy R & D Goals Study*, a Report of the Federal Technical Group on Electrical Transmission and Systems (July 14, 1972).

In sum, we argue that generation and transmission functions should be separated from distribution. Favoring diversity, and concerned about undue concentration, we would favor the creation of multiple regional power suppliers, each of which would be certificated by a supervising regulatory authority (our regional commissions or the FPC). In this way it would be possible to achieve the benefits of competition (including yardstick competition), a preferred position in the capital market, and the availability of the highly trained technical experts so essential to the planning and daily operation of sophisticated generation and transmission facilities. Even this degree of concentration poses problems. It will only be tolerable if the supervising regulatory authority (and the public counsel we urge be established) has sufficient independent expertise (financial as well as technical) to undertake a complete independent review of company presentations.

NATURAL GAS INDUSTRY EXPERIENCE

In case of the natural gas industry, separation of production and distribution functions may well have contributed to the current shortage situation. Natural gas production companies, being highly diversified international operations, dedicate their capital where the return appears most promising; thus natural gas exploration may suffer as a consequence. We would protect against the repetition of this difficulty in the electric power industry by prohibiting any diversification by generation and transmission entities.

The ability of the smaller, independent natural gas producers to have a significant impact on supply has lessened considerably as production moved to offshore areas. In view of the Interior Department's leasing procedures (which require the payment of bonus amounts for large tracts of land well before any production can commence) and the high cost of drilling offshore, it apparently is difficult even for the major oil companies to operate offshore without joining together in drilling combines.

With the separation of distribution entities, the ability of state commissions to discharge their regulatory functions should be enhanced markedly. The separation of generation and transmission activities from distribution would remove most of the complex allocation problems that now often overwhelm commissions, particularly at the state level. In short, effective regulation should be promoted on all levels while securing the benefits of local management and maximizing competitive diversity particularly in the area of ultimate consumer service. This separation is not entirely novel, even in this country. It is the situation that prevails in large parts of the Bonneville and Tennessee Valley Authority service areas. Further, it is the pattern followed in Great Britain and in parts of Canada.

We are not alone in recommending a realignment of the electric power industry. In a 1970 report prepared for the New England Regional Commission it was concluded that "the best ultimate answer for New England is a single bulk power supply agency with full responsibility for the generation and transmission of electric power."[4] As conceived, the new agency would have sole authority to construct future generation and transmission facilities, possibly subject to some separate site certification authority, and might or might not begin by the acquisition of existing facilities as well. As alternative models the report suggests "a multi-state agency or a private corporation, perhaps with federal involvement along the lines of the Comsat precedent" (pp. 21–22), and a regional site acquisition authority patterned after the New York Space and Atomic Development Agency, which is charged with the acquisition of nuclear power plant sites in that state. The regional agency would make payments in lieu of taxes to state and local governments and would be excused from the need to comply with the licensing requirements of state or federal environmental standard setting agencies.

We have already addressed our objections to the merger of environmental standard setting and licensing responsibilities. As to the matter of taxes, we agree that payments should be made to local authorities as compensation for lost tax base. Persons who reside in the vicinity of generation and transmission facilities will bear most of the brunt of external costs and these also should be compensated. Reduced property taxes would appear to be a politically acceptable form for such payment. While it may be that one would be hard pressed to find a taxpayer who is not also a consumer of electricity we do not all consume at the same level. Second, removing local tax base would surely impose a significant additional siting obstacle.

More recently, Huettner and Landon have proposed that the electric power industry be reconstituted so as to parallel the structure of the natural gas industry—that is, by the creation of separate production, transmission, and distribution segments.[5] Except in remote areas, no vertical integration would be permitted. The generation segment would be deregulated; the transmission segment would be placed under somewhat expanded FPC regulatory control; and the distribution segment would remain subject to local regulation. It is assumed that the generation segment would become competitive and would sell its output to distribution entities pursuant to long term (five-year) contracts. In securing supplies, distributors would seek competitive bids from the independent producers. Transmission entities would be required to operate as common carriers accessible to all producers and distributors.

We do not agree with the willingness as expressed in the New England report, to concentrate responsibility for future power supply in a single entity, public or private. We are committed to the view that regulation is not a substitute for competition and that management diversity is essential to the achievement of optimal efficiency, particularly in an industry beset by novel economic, technical, and social difficulties and facing a wide spectrum of future options.

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[4] *A Study of the Electric Power Industry in New England 1970–1990*, The New England Regional Commission, September 1970, p. 16.

[5] David A. Huettner and John H. Landon, *Restructuring the Electric Utility Industry: An Economic Analysis.*, presented at the Seminar on Problems of Regulation and Public Utilities, Amos Tuck School of Business Administration, Dartmouth College, Aug. 29, 1973.

POWER PRODUCTION COMPETITION

We share the Huettner/Landon predisposition toward the stimulation of a competitive thrust at least in the power production segment. The argument that electric utilities are "natural monopolies" is based, insofar as generation is concerned, on the existence of economies of scale. There is, however, a limit to economics of scale which tends to stimulate competition among several generating firms within each region. Present indications are that most economics of scale are reached at about the 600 MW level and few persons are optimistic about technological breakthroughs over the next decade which will serve to significantly push that level up. In view of the fact that the optimal unit size may be quite moderate (particularly if there is a desire to reduce reserve requirements which must contemplate the loss of the largest units), new entry by smaller firms is quite likely providing guaranteed access to the transmission grid exists. Indeed the existing technological fix may make new entry by independent firms a natural (rather than legislatively required) phenomenon.

We cannot accept their implicit assumption in favor of free entry or their sanctioning of total deregulation in generation. They recognize that with free entry the bankruptcy of generating companies will be expected occurrences. Generation companies, particularly new entrants, either because of their inability to cope with rising capital costs or construction delays or because of their desire to win supply contracts, will be induced to offer bids which are unrealistically low, which in turn will hamper their ability to fulfill contractual commitments. Huettner and Landon assume that a combination of performance bonds and the existence of adequate reserves (presumably available from other generation entities) will adequately protect both the distribution company and its ultimate consumers. We do not agree. To be sure performance bonds, warranties, long term contracts, and similar devices—including perhaps a form of "futures market" in generating capacity—may be used to foster market stability. The critical position of the electric power industry in the economy requires that these be complemented by regulatory guarantees of adequate electrical supply.

A distribution entity would most likely contract with its sole wholesale supplier for a desired reserve margin in order to avoid the economic penalty associated with being a low load factor customer of a second supplier. Presumably this difficulty could be lessened by each bulk power supplier agreeing to serve as a reserve (or backup) supplier for the customers of a competitive producer. But it is difficult to conceive of this possibility if the industry is truly competitive. Moreover, we are hesitant to sanction the need for what easily could be collusive arrangements particularly since under the Huettner/Landon model the power supply segment would be unregulated. We also suspect that this procedure would serve to exacerbate reserve requirements resulting in related economic and environmental costs.

We therefore cannot agree that the bulk power supply segment should be freed of federal (or regional) regulation. Perhaps after experience is gained under the intermediate step we offer, such a suggestion would be worthy of consideration. But there must be the assurance that there would be active competition between relatively equal contenders for wholesale business, and wholesale customers must in fact have access to competing suppliers through a nationwide high voltage transmission network. While the possibility exists that such a network could be developed following perfection of now experimental underground transmission technologies it is premature to assume free access in advance of the availability of at ransportation system in place.

Deregulation of bulk power suppliers could introduce a new measure of unaccountability. Free market competition can be effective in maximizing efficiency, where the measure of efficiency is confined to private costs. But in the case of electric power plant siting and operation it is not adequate to be concerned with "price" competition alone; our current problems are due in part to a failure to recognize externalities or social costs. Such factors cannot easily be worked into a system governed solely by marketplace competition. This could be particularly true when the bulk power supply, having no direct service dealings with ultimate consumers, has no direct public accountability.

It might be possible to partially offset this failure to account for externalities by having a public agency develop a social dollar cost for each bulk power supply site. Should a supplier wish to construct on that site it would have to pay a tax equivalent to the assigned social cost or, alternatively, make an equivalent contribution into an externality fund. Since these added costs would have to be reflected as production expenses, there would be incentive to minimize them by selecting sites that bring with them the least externalities. Even if dollars are not transferred it is important to develop a site bidding system that includes social as well as private cost considerations. However, even this partial response requires site regulation, at a minimum. The operation of "social cost" regulation beside a competitive industry structure is not without precedent. It certainly applies in the case of the drug and consumer products industries through the existence of the Food and Drug Administration and the Consumer Product Safety Commission.

Under the Huettner/Landon model state regulation would continue for distribution entities but competitive bidding alone would, from the outset, govern the wholesale price of electricity. This total absence of regulatory review on the bulk power level would introduce several complications, however. In view of construction lead times, supply contracts would have to be let five to seven years in advance of actual production. When is the local commission to regulate this element of distribution expense? If it is to take place at the time bids are solicited and accepted, regulation will be meaningless.

The industry has not been able to realize anticipated power supply costs. If the costs escalate dramatically during the construction period, or local regulatory review is postponed until the capacity is on line, there would be little opportunity for meaningful rate oversight. It is unlikely that distributors would be able to find alternative sources of supply at the late date. Indeed, it is quite likely that bulk power suppliers will require price escalation clauses as a hedge against unanticipated cost increases.

While it is fine to argue that they should be made to compete on a firm price basis, to do so will either magnify the bankruptcy problem, inhibit free entry, or result in higher contingency margins in all bids. Regional commission regulation of entry through the comparative analysis approach would afford a more meaningful opportunity to assess cost projections. Most important, it would overcome the social problems that arise when competition only addresses private costs. Without regulatory review it does not appear possible to insure that competition alone would encourage the minimization of externalities.

We accept the proposition that the transmission segment, whether or not it is separated from production and distribution, should be converted to common carrier status. However, this can be accomplished under the present industry structure and we believe it should be, whether or not more basic structural alterations are pursued. For example, all extra high voltage transmission facilities (say 230 Kv and above) could be placed under comprehensive FPC jurisdiction. Capacity in excess of the short, intermediate, or long term needs of its owner would be available, pursuant to FPC regulations, for use by any generation and transmission entity.

Contracts for a specified term would be tariffs filed with the Commission. Further, any utility should be free to expand, at its own expense, the transmission capability of another utility's corridor, either by upgrading the capacity or capability of existing facilities or adding circuits where feasible, or paralleling with new facilities, providing that it does not unduly impair the operations of the owner utility and that such owner is compensated for all reasonable costs (possibly including lost options) it will suffer.

By "free to expand" we mean pursuant to an application file with, and approved by, the FPC. It is our expectation that many of the advantages of common carrier status could be achieved through pooling and more aggressive FPC coordination and rate review initiatives. Certainly the realization of these objectives would be a prime responsibility of the regional commissions as they develop regional coordination plans.

However, there are arguments that can be made for retaining the merger of the generation and transmission segments. Their separation would introduce several practical problems. How would a generation entity be able to plan its expansion program, with its seven to ten year lead time, if it has no control over the availability of transmission? How can distributors solicit bids from producers without integrating transmission availability and cost considerations? How is a producer to practice economy dispatch without control over the transmission network? And how do you account for the fact that power flow cannot be routed with precision over any particular path particularly in the event of an unexpected outage?

The natural gas analogy is not fully applicable. A natural gas producer, if denied access to a pipeline transportation system, simply caps the well and bears relatively nominal carrying costs. The economic penalty that would have to be borne by a generation entity denied access to a transmission system capable of serving its loads (if only because excess capacity is not available) would be disastrous. Also, sharing reserve requirements is a necessary condition for the future electric power industry. Technical failures in the electric power industry are quite different from natural gas production shortfalls.

Thus far we have avoided the recurring debate over the appropriateness of affording public power systems the preferential treatment inherent in federal or tax free financing. Without belaboring the point our initial prejudice is against subsidies, particularly where they are exacted from the public generally in favor of a more limited consuming group. However, in past years those subsidies were essential to accomplish an overriding social objective: to bring the advantages of power to large segments of the population not being served by the private sector. It was also important to develop an economic yardstick.

Today, as our concern shifts more toward issues of social accountability, the importance of the yardstick concept remains and perhaps enjoys new prominence. It should be noted, moreover, that the economic advantages do not flow only to the public power sector. Rural electrification funds were never limited to cooperatives. Private utilities were free to apply and receive them. The only limiting condition was that REA financing was limited to supplying service to rural areas. Today privately owned utilities are making increasing use of public tax free financing through the issuance of pollution control bonds. By the end of 1972, there were 52 such bond issues averaging $11 million apiece.[6]

Obviously the presence in every region of a strong federal marketing agency (if its influence were properly directed) could go a long way toward securing regional coordination objectives as Bonneville has accomplished in the Pacific Northwest. Such a federal presence would also help secure the continued vitality of small investor owned and public systems that are now at the mercy of single source suppliers. Finally, the yardstick influence of regional marketing agencies could be most significant, particularly if those agencies are committed to sound environmental management. For these reasons, and in view of the need for a bulk power supplier willing to implement a regional scenario, should the private entrants decline so to do, we would hope that one of the regional suppliers under our proposal would be publicly owned. In several cases this would easily be accomplished by simply reconstituting existing federal marketing agencies.

INTERACTION

A final comment about the interaction of our proposed regulatory and industry restructuring. We recognize that we may well be replacing vertical monopolies with several giant production combines. However, the assumed prejudice of this arrangement would be largely offset by the presence of an independent public bulk power supplier and the creation of an effective regulatory mechanism. Moreover, it would not be necessary to forgo the advantages that may accrue to a distributor (and to society generally) from being able to obtain a power supply from a producer in a remote region.

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[6] See John Winders, "Tax-Free Anti-Pollution IRB's Head Toward 1 Billion Dollars in '73," *The Bond Buyer,* March 14, 1973.

As part of its planning function each regional commission, working through the National Coordinating Commission, would be expected to maximize the benefits of time diversity by requiring that the alternative of purchasing from outside of the region be substituted for expansion of regional capacity. Hopefully, the entire nation will thereby share the benefits of reduced social and private costs, as would occur where a region makes use of far distant geothermal capacity in lieu of adding its own peaking facilities.

THE UTILITY INDUSTRY—II

(By Morgan Guaranty Survey)

The conventional approach to electric power, based on the experience of seeing each new addition to the grid produce power at a lower price than the previous capacity, has been to sell as much power as the market will take and build as much plant as there is money available to build it. Electric power translates to industry and jobs, which translates to prosperity. The corollary to this approach is that lack of electric power means economic decay. If planned additions to capacity do not meet projected demand, more plant must be added.

The next selection presents this conventional approach, modified slightly to accomodate the new emphasis on conservation that is gradually reaching a broad part of American society. It is interesting to note how quickly the electric power scene is changing: The arguments in this selection are based on a projected growth rate in demand of "6 percent or a little less over the next decade"—much higher than most projections less than a year after it was written.

It is important to recognize that the conservation efforts advocated in this article are aimed at preserving the system from blackouts and supplying needed electricity for prosperity-stimulating uses. The main thrust remains to build and use as much electric power as we can afford. It is a far cry from the approach of Lovins, which is to build and use as little electricity as we can possibly get by with. The two articles represent the gap between the thinking of major sectors of the debate over future electric power generation.

[From the Morgan Guaranty Survey—January 1978]

WHEN WILL THE LIGHTS GO OUT?

Last May, a massive power failure struck Southern Florida, cutting off electricity in a 15,000 square-mile area for periods ranging from a few minutes to several hours. More than 3 million businesses and households were affected. Although there were no major accidents, injuries, or incidents, many schools and businesses were forced to close and automobile traffic was snarled.

Last July, in New York City, it was much worse. A power blackout, lasting 25 hours in some areas, stopped commerce, stymied transportation, turned high-rise apartments into prisons, and made water a luxury. Subways rolled to a stop. Elevators were stranded in their shafts. Water pumps failed and with them tubs, sinks, and toilets. In a "night of terror," thousands looted and burned. Estimates of property losses ran into the hundreds of millions.

For Americans, accustomed to high-quality electric service, such massive blackouts—caused by weather or mechanical malfunction—come as a shock. Rare, it's true, they have been. But what of the years ahead? Is a much more basic problem—a serious shortage of generating capacity—soon to grip America as it does so many less-developed lands?

The power picture, unhappily, is far from rosy; indeed, unless corrective steps are taken soon, the outlook for the nation's electric power supply is quite threatening. One energy analyst, not known for making wild statements, nonetheless is on record as predicting a "hair-curling" power crisis in 1985. Some experts in the utility industry place the critical years in the late 1980s. But many other authorities expect trouble even sooner: brownouts and blackouts are forecast in the Southeast as early as 1979 and in the Midwest in 1980. Failures caused by lack of capacity are seen spreading and increasing in severity as the Eighties wear on.

Such gloomy forecasts, if they turn out to be anywhere near the mark, could have significantly adverse effects on commerce, industry, and the transportation system of the nation.[1] There is a strong link between energy consumption and economic growth. Rising unemployment would be only one of many personal hardships for many thousands of Americans.

No worker, using his muscles alone, can produce in one day the energy represented by one kilowatthour (kwhr) of electricity. The Edison Electric Institute estimates that a manual worker in a year's time expends energy equivalent to about 67 kwhrs. Factories, of course, boost that productive power through use of electricity. In

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[1] Industrial clients are the heaviest users of electricity (39 percent of kwhr sales). Residential customers account for 33 percent of electric sales: commercial, 24 percent; and "other," 4 percent.

In numbers, of course, residential users are dominant. In mid-1976 there were 73.1 million residential customers (89 percent of the total); 8.7 million commercial (10 percent); 430,000 industrial (0.5 percent; and 271,000 "other" (0.4 percent).

1974, for example, a factory worker used, on average, just under 48,000 kwhrs of electricity—in effect, the energy equivalent of 715 men helping that worker on the job all year long.

The table on page 8 shows the steep rise that has taken place over the past decade in electric energy used by U.S. factories. Transformed by electricity, too, have been the nation's farms, its homes, its very way of life. As levels of living have risen, so, not surprisingly, has output of electricity. Indeed, with less than 6% of the world's population, the U.S. produces almost as much electricity as the next four countries combined—Russia, Japan, West Germany, and the United Kingdom.

From the 1880s until 1970, electric power requirements of the U.S. grew at an average annual rate of about 7 percent. In the mid-1960's the Federal Power Commission (FPC) saw everything coming up roses: abundant supplies of electricity and a continued decline in the cost of electric power (table on page 9).

In the past few years, the picture has changed rather sharply for the worse. By 1973, FPC experts had grown increasingly concerned about rising costs of producing electricity and about serious threats of power shortages.

ELECTRICITY USED BY THE U.S. WORKER

	Production workers in manufacturing (thousands)	Kilowatt-hours per year used by manufacturing industries (millions)	Average kilowatt hours per worker per year
1974	14, 613	700, 013	47, 903
1973	14, 760	694, 107	47, 026
1972	13, 957	645, 862	46, 275
1971	13, 434	597, 441	44, 472
1970	14, 020	584, 096	41, 662
1969	14, 767	580, 367	39, 302
1968	14, 514	541, 661	37, 320
1967	14, 308	505, 821	35, 352
1966	14, 297	479, 890	33, 566
1965	13, 434	453, 881	33, 786
1964	12, 781	437, 032	34, 194

Source: Edison Electric Institute.

Adding to the concern—beginning in 1974—was a string of power plant (conventional and nuclear) postponements, cancellations, and indefinite deferments. By mid-1977, some 288 proposed power plants had fallen temporarily or permanently by the wayside, and new-order books of firms that make nuclear power plants have been nearly blank for the past couple of years. As it takes more than twelve years to build a nuclear power plant and at least seven years to build a coal-fired plant (twice as long as it takes in Europe because of U.S. environmental and procedural regulations), the urgency of the situation is abundantly clear.

A host of problems have hit the powerhouse hard in recent years. Labor costs for construction have mounted steeply. So have financing costs for the most capital-intensive of all industries. Cash flow problems, meanwhile, have mounted, owing in important part to "regulatory lag"—i.e., by the time that regulators have approved a rate increase, inflation has invalidated the "test year" data on which the increase was based.

A major hurdle for the industry is securing licenses from regulatory authorities, a task which has become infinitely more complex and time-consuming with stringent new environmental criteria. For example, in California no fewer than 91 permits from 43 agencies are required for one nuclear plant. Moreover, new statutory and regulatory requirements for both fossil and nuclear plants—at the federal, state, and local levels—have added significantly to the cost of building such units. A recent study by Ebasco Services, Inc. estimated that in 1969 a nuclear plant could have been installed for $160 per kilowatt, compared with $122 per kilowatt for coal. During the next seven years, inflation pushed up building costs $142 per installed kw for nuclear plants and $99 per kw for coal-fired plants. However, increases in plant costs due to statutory and regulatory changes were $374/kw for nuclear power plants and $327/kw for coal—roughly three times the increase in costs due to inflation. All the while, public protest groups have grown ever more active, forcing delays—often measured in years—in securing power plant sites and transmission line clearances.

Easing the pressures on the nation's electric companies has been a reduced rate of growth in power demand. In the past few years, a combination of conservation by the public and by industry and commerce,[2] the increased cost of electricity, and the steepest recession in 40 years held growth in power demand below the earlier trend. Many of those same forces—conservation, higher prices, lower rates of growth in population—could bring about a reduced rate of rise in power demand in the decade ahead. Some utility experts, for instance, are forecasting a compound growth rate in annual power demand for the nation as a whole of 6 percent or a little less over the next decade, as against the historic 7 percent growth. (In some areas of the country the projected growth figures are as low as 2 percent per year.) And yet, other experts in the industry tend to doubt such a decline. They see an added power load for electricity growing out of efforts to replace oil and natural gas with other power sources in such uses as space heating and from government efforts to speed up industrial expansion to provide more jobs.

Though the experts may differ over expected growth rates in electrical demand, all agree that the industry faces a difficult task. And, as indicated earlier, there is substantial uncertainty—in and out of government—about the industry's chances of meeting the challenge.

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[2] An industry example of conservation was reported recently at AT&T. In the first nine months of 1977, the Bell System used 11 percent less energy than was consumed during the same period in 1973—even though the volume of business increased 45 percent and the number of telephones served rose more than 16 percent.

ELECTRICITY: WHAT IT COSTS RESIDENTIAL CUSTOMERS

	Average kilowatt-hours used per residential customer per year[1]	Average revenue per kilowatt-hour (cents)	Average annual bill
1975	8,176	3.21	$262.65
1970	7,066	2.10	148.39
1965	4,933	2.25	110.99
1960	3,854	2.47	95.19
1955	2,773	2.65	73.48
1950	1,845	2.88	53.14
1945	1,229	3.41	41.97

[1] Alasia and Hawaii included since 1960.

Source: Edison Electric Institute.

The key consideration, all analysts agree, is the size of the so-called reserve margin—the amount of installed generating capacity in the nation in excess of peak load demand. This should not be considered purely excess capacity. A large portion of the reserve margin is needed to permit scheduled plant shutdowns for maintenance and overhaul, to allow for unexpected extremes in weather (hot or cold), and to provide a "cushion" of power to be drawn upon in the event of an emergency surge in demand (or a major generating problem) in, say, a neighboring power system. Reserve power margins at the time of summer peak demands have been running around a comfortable 30 percent in the past couple of years on a national average basis, helped by the reduced growth in power demand. The FPC report sees that reserve margin dropping to about 21 percent in 1986—still a reasonably safe margin for the nation.

However, such a reassuring forecast, as the FPC is quick to point out, depends heavily on several major "ifs"—if projected generating capacity levels are actually attained, if fuel requirements are met, if no more than the normal contingencies are experienced. And, the FPC experts doubt that all the "ifs" will fall neatly into place and assure an adequate power supply.

Nuclear generating capacity, for instance, is falling far behind schedule. Originally, industry projections for nuclear units for 1977–86 showed additions of 131,000 megawatts (a MW is 1,000 kilowatts) in 121 new units. But now the Nuclear Regulatory Commission (NRC) projects an increase of only about 90,000 MW in 84 units. The difference of 41,000 MW represents a significant decrease in available capacity in the decade ahead.

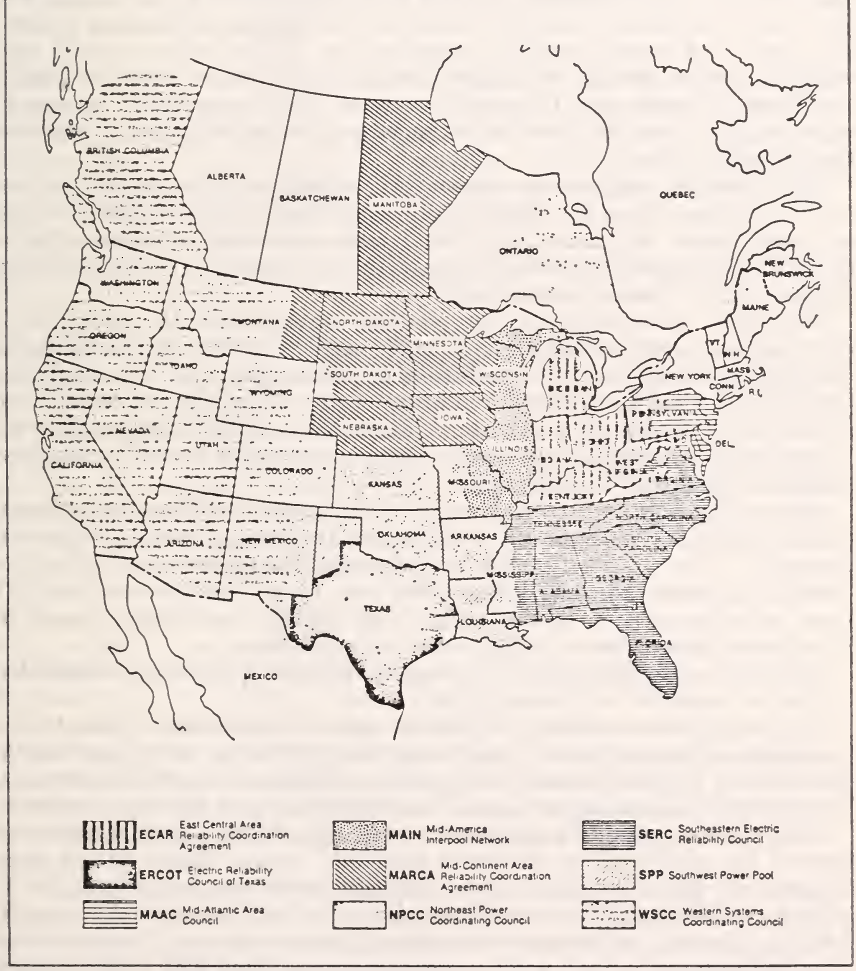
Warns the FPC: "If the NRC projection proves correct, and the projected demands materialize, the 21.4 percent reserve margin forecast for summer of 1986 would be reduced to 14.9 percent. This reserve level is considered too low to assure an adequate and reliable electric power supply nationally."

After 1986 the picture is even bleaker because of the long lead time (twelve years) for nuclear power plants. Major U.S. manufacturers of such plants estimate that no more than 5,000 MW of capacity will be ordered in the U.S. in 1978. Unless there is a major streamlining of siting and licensing procedures, these plants will not be operational until at least 1990. It is interesting to note that the New York State Power Siting Board, created as a model "one-stop" siting agency in 1972, approved its first plant site five years later.

Shortages of power for the nation are seen hitting some parts of the country sooner—and harder—than other parts. The regional pattern of power systems is shown in the map on the opposite page. It covers the nine Regional Reliability Councils, which encompass essentially all of the power systems of the U.S. and the Canadian systems in Ontario, British Columbia, Manitoba, and New Brunswick.

With the power picture reduced to nine acronyms, the reader can know exactly where government and private power experts see trouble looming ahead. The accompanying table shows when the various regions seem likely to begin experiencing an inadequate power supply situation. A critical shortfall is seen in SERC in 1979. In 1980, MAIN will feel the power squeeze, followed in 1981 by ECAR and SPP.

Nine Regional Power Systems


BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
QUEBEC
NEW BRUNSWICK
WASHINGTON
OREGON
MONTANA
IDAHO
WYOMING
NORTH DAKOTA
SOUTH DAKOTA
MINNESOTA
WISCONSIN
NEBRASKA
IOWA
NEVADA
UTAH
COLORADO
CALIFORNIA
KANSAS
MISSOURI
ILLINOIS
ARIZONA
NEW MEXICO
OKLAHOMA
ARKANSAS
TEXAS
MISSISSIPPI
LOUISIANA
ALABAMA
GEORGIA
FLORIDA
TENNESSEE
KENTUCKY
NORTH CAROLINA
SOUTH CAROLINA
VIRGINIA
WEST VIRGINIA
OHIO
MICHIGAN
PENNSYLVANIA
NEW YORK
DEL.
MAINE
VT.
N.H.
MASS.
CONN.
R.I.
MEXICO
ECAR East Central Area Reliability Coordination Agreement
ERCOT Electric Reliability Council of Texas
MAAC Mid-Atlantic Area Council
MAIN Mid-America Interpool Network
MARCA Mid-Continent Area Reliability Coordination Agreement
NPCC Northeast Power Coordinating Council
SERC Southeastern Electric Reliability Council
SPP Southwest Power Pool
WSCC Western Systems Coordinating Council

SOURCE: The National Electric Reliability Council

Evaluation of reserves for higher load growths and delayed capacity additions

Region:	*Year when generation deficit could begin*
ECAR	1981
ERCOT	1985
MAAC	1985
MAIN	1980
MARCA	1983
NPCC	1983
SERC	1979
SPP	1981
WSCC	1986

Source: National Electric Reliability Council.

Projecting future power availability—or potential power inadequacies—is a risky business fraught with unknowns. For example, no shortage of electrical generating capacity is expected in Western states. And yet that area—heavily dependent on water power—could experience severe energy shortages beginning this year if the drought continues. Recent precipitation has eased water conditions in many parts of the West, but weather experts as yet are reluctant to declare the drought ended.

Many power analysts question the soundness of including in the nation's power base the nearly 300 fossil-fired plants which already are more than 40 years old. Could such relatively obsolete plants perform adequately in coming years in an atmosphere of mounting demands and strained capacities?

Moreover, power-capacity projections assume that the older coal-fired plants (many of which are under attack by the Environmental Protection Agency on air pollution grounds) and the gas and oil-fired plants that the government may order to be converted to coal will actually continue to operate. If such plants should not be allowed to continue functioning, the nation's power reserve would inevitably shrink below today's projections.

A stop-gap solution to make up for obsolescent coal and gas power plants would be to hook up combustion turbines to meet peak-load demands. The obvious drawback, however, would be that such turbines, which can be installed quickly and at a relatively low capital cost, are expensive to operate and they would use oil and gas at a time when the nation needs to conserve such fuels.

Against a background of potential electric power curtailments, action is called for on three fronts:

1. Conservation efforts, especially among consumers, need to be intensified. Some success in curtailing the growth in use of electricity has already been achieved—due mostly to higher prices for electricity. But energy analysts agree there is considerable room for improvement.

Polls and surveys of consumers reveal a startling lack of awareness among the public as to the most simple of energy facts. Many consumers are not aware that lower wattage bulbs use less energy. Still others, numbering in the millions, have no real idea of the energy load of various appliances in the home. As an example, nearly half of the respondents in one survey were unaware that the water heater is the biggest user of electricity in the home. The accompanying table shows the number of kilowatt-hours consumed by some of the major appliances.

Power in the Home:	*Kilowatt-hours consumed annually*
Broiler	85
Coffeemaker	140
Dishwasher	363
Hot plate	90
Range:	
With oven	700
With self-cleaning oven	730
Trash compactor	50
Freezer:	
Manual defrost	1, 190
Automatic defrost	1, 820
Clothes dryer	993
Water heater	4, 219
Air-conditioning (room)	860
Hair dryer	25
Television: Color (tube type)	528
Vacuum cleaner	46

Source: Edison Electric Institute.

Many consumers are found to be suspicious that the energy crisis is no more than an artificial creation of the oil companies and politicians. And among those who concede that energy is—or will be—a problem, there is a feeling that, somehow, technology—rather than private acts of conservation—will provide the magic solution. The burden of educating the consumer must be shared by the utilities.

2. The supply side of the electrical energy equation needs urgent attention. Here, a major consideration is a streamlining of often conflicting and overlapping government regulation of power plant siting, licensing, and construction.

The National Electric Reliability Council (NERC) complained recently that at the state level the regulatory and certification process has become increasingly fragmented by a variety of agencies. In addition to the Public Utility Commission, or its equivalent, there may be separate plant siting commissions, state environmental protection agencies, state energy commissions, and land-use commissions—all requiring independent hearings. At each step in the approval process there is opportunity for intervention and challenge, and the same case has to be proved over and over again.

NERC sees a compelling need for Congress and the states to establish a mechanism for "eliminating duplicative hearing procedures, resolving conflicts between agencies, establishing reasonable but strict time limits for action by the agencies, and obtaining final and irreversible decisions on the siting of generating plants."

The public interest, to be sure, needs to be protected. But it should also be a major concern of government that its regulatory procedures not needlessly impede an adequate supply of electric energy. President Carter, recognizing this, has promised to speed up licensing of nuclear power plants, but many in industry are skeptical that major improvements will be made.

3. Financing power plants for tomorrow is a hurdle today for many of the nation's electric utilities. Common stocks of many utility companies are selling at or below book value—hampering the raising of equity capital. Moreover, in some cases, debt financing possibilities are severely limited because interest coverage ratios are inadequate.

Spiraling costs (construction, financing, operating), meanwhile, have added to the utilities' financial burdens.

With the long leadtime of 7 to 12 years for power plants, utilities must commit huge amounts of funds without knowing when they will begin earning a return on their investments. In all too many cases over the years, utilities have put up huge amounts of money only to see delays eat up additional millions of dollars. A recent example is Seabrook, a $2.3 billion 2,300-megawatt nuclear plant which is expected to supply 80 percent of New Hampshire's power requirements. Environmental studies began in 1969, but last year construction was halted when an EPA regional administrator reversed an earlier approval. The cost to the company and its customers of the delay was estimated at $15 millon a month prior to resumption of construction earlier this year.

AN ENERGY-LIMITED ECONOMY?

All in all, electric utilities as a group are facing a potential financial squeeze which could threaten their ability to deliver adequate power-supply facilities.

Prompt and adequate rate relief is vital. Although there has been improvement in this regard by some state commissions in the last two years, regulatory authorities in several states have failed to allow the increased rates needed to keep the utilities in sound financial shape.

The utility commissions are, and should be, responsive to the plight of many electricity users living on fixed and relatively low incomes. But there is an increasing need for everyone to recognize that failure to face up to the needs of a healthy, viable electric power industry risks jeopardizing the country's economic future. Clearly, what is threatened is an energy-limited economy, with disrupted factories, crimped farms, underemployed workers, lagging growth in GNP, and reduced levels of living.

Many analysts view the "no growth" concept fostered by environmentalists as a way to bring about a fundamental change in American values and in life styles. Whatever the motive, it is unfair for such groups to impose their value system on society when many millions of its citizens want economic growth and opportunities for personal advancement for themselves and their children.

THE UTILITY INDUSTRY—III

(By John Wicklein)

This selection illustrates the strength of feeling that lies behind the dependence of large urban communities on reliable electric power supplies. In discussing the 1977 New York City power failure, Wicklein blames Con Ed, and secondarily the Government for not forcing the utility to secure its interconnections with other utilities. Con Ed, of course, says that it should be allowed to build more plants. An interesting aspect is Wicklein's demand for a national power grid, a topic that is discussed in the next selection.

[From The Progressive—November 1977]

MUST WE TRY FOR BLACKOUT III?

(By John Wicklein)

New York did not go black the night of July 13 because God smote Consolidated Edison with lightning. New York collapsed because, ever since Blackout I in 1965, some short-sighted men at Con Ed have refused to take the engineering measures that would ensure that the system would not collapse again. It did collapse, and at an economic and social cost far greater than the engineering steps the company should have taken to protect against a new disaster.

Con Ed is not alone in its inertia. When reporters pressed power company executives in other urban centers with the question "Can it happen again?" they did *not* say flatly, "It can't happen here." It can. Considering the standards of reliability under which most companies operate—standards little changed since the Northeast blackout of 1965—we probably will see (or grope around in) Blackout III.

The Consolidated Edison Company is the biggest private power system in the world. Yet, when the emergency came, it could not save itself. *No* single system can save itself from blacking out. At the time this most recent emergency hit, Con Ed was drawing one-third of its power from outside its system.

For reliability, a power system must, at normal peak periods and in emergencies, be able to draw instantly not only on its own reserves, but also on the reserves of other systems in its region. To do that, the local system must be heavily interconnected at many points to many other systems.

When the chips were down (or, as Con Ed had it, when lightning struck), the utility that had been granted a monopoly to supply electricity to 9,000,000 people in New York City and Westchester County was relying on only four interconnections to bring in about 2,000,000 kilowatts of power—out of a total load of 5,800,000 kilowatts—from outside sources. Only one of the four, a 500-kilovolt line that ties the utility in with the Pennsylvania-Jersey-Maryland power pool and the New York State power pool, would be considered major by standards of the large American Electric Power Company network in the Midwest or several of the national systems of Western Europe.

Power from this line was interrupted, according to Con Ed, when two high-voltage lines carrying its output and that of Indian Point Three nuclear power station were struck simultaneously by lightning at 8:37 P.M. At 8:56 P.M., according to Con Ed, two more lines, carrying 1,000,000 kilowatts of power from the New York pool, to which it belongs, were also taken out by lightning. From that time on, the system was doomed. Con Ed had insufficient reserve capacity to make up for power denied it from the west and north, and no alternative lines to draw power from these sources of supply. In this emergency, one additional high-voltage connection to the P-J-M or New York pools, both of which had power to spare, could have kept most of the city from being plunged into darkness.

The answer seems obvious—Con Ed should have built more heavy interconnections than it had in operation on July 13. In fact, that answer has been obvious to many investigators and system engineers since the blackout that brought down New York, New England, and parts of Canada on November 10, 1965.

To guarantee the availability of electricity, local power distribution systems must be fully integrated into large regional or national grids in which power is controlled and dispatched from a central point that has knowledge of the energy situation in every part of the region.

Large, tightly interconnected grids are standard engineering practice among electrical utilities in Western Europe. In England and Sweden, national grids tie all power plants together. All the plants of France, West Germany, Belgium, and the Netherlands are tied into an international grid. Officials of these systems, queried by the Associated Press after the New York disaster, said they considered massive, cascading power failures to be an American phenomenon. In the United States, large, centrally dispatched regional networks are the exception rather than the rule.

Most power companies in the United States maintain "spinning reserve" (generators fired up, but not connected into the system) equal to the largest single generating unit that could go down, and one major high-voltage line for backup. (Con Ed said it had this amount of generating capacity in reserve on July 13; it did not have the reserve transmission line.) A multiplier effect in reliability can be achieved by tying the individual systems, with their reserves, into a centrally controlled regional grid. Thus, all the spinning reserves are immediately available, to be used to meet unexpectedly high peak loads of one or more members of the interconnected system, or to send power instantly, over multiple paths, to a system that has lost capacity through the breakdown of a generator or a transmission line.

This arrangement also provides a financial benefit. In England and Sweden, the grid dispatchers bring the most efficient plants on line first, then cut in others in descending order of efficiency as the load increases. In the absence of a grid, companies in the United States have to operate their more costly plants a larger part of the time. If this country's electrical capacity were tied together into an integrated system, estimated power reserves would mount up to 24 per cent of the national demand.

Looking through the post-blackout edition of The New York Times of November 10, 1965 (its eight-column head was "Power Failure Snarls Northeast") gives you a sense of deja vu:

"U.S. Orders an Inquiry/President Calls for a Study of Power Failure in East"—The Times, November 10, 1965.

"U.S. Inquiry Ordered"—The Times, July 15, 1977.

The President who ordered the inquiry in the first story was Lyndon B. Johnson; the Federal Power Commission (FPC) submitted its report to him on July 19, 1967.

In the 1977 blackout the President was, of course, Jimmy Carter. He, too, asked the FPC to find out why the blackout happened, and to recommend "specific actions" to prevent another. President Carter might find the answer in the first report.

"Given the percentage of power Con Ed draws from outside the system," John Ahearne of the President's Energy Policy and Planning staff told me, "they seem to be poorly prepared for the emergency in terms of interconnection." That's what the 1967 FPC report said.

On July 18, President Carter also asked his Cabinet and the FPC to investigate a possible national grid system that would allow a more orderly and structured transfer of power to an imperiled system on an emergency basis.

President Carter's energy program does not propose the establishment of a national grid, but does include provisions that would strengthen regional interconnections and pooling of power reserves.

The FPC report to President Johnson said the key lesson of the 1965 Northeast failure was that interconnection and coordination of diverse power systems "must be strong to be effective." The report stated:

"Transmission must be recognized as the principal medium for achieving reliability, both within a system and through coordination among systems. It is the cohesive force which ties together power systems. Cascading power failures are usually the result of insufficient capability within the transmission links of a system or group of systems to withstand the sudden demands placed upon them by reason of disturbances arising within or without the system."

That last sentence describes precisely the predicament in which Con Ed found itself the night of July 13. Yet three days earlier, Charles F. Luce, chairman of the company, said in an interview that he could "guarantee" that the chances of another blackout like the one in 1965 were remote.

"No management," said the FPC report, "can avoid its share of the responsibility for building adequate interconnected transmission systems."

The report recommended that utilities establish coordinated programs of automatic load-shedding to prevent the total loss of an area that is deficient in generation. In such programs, areas of low priority—usually low-density residential—are dropped from the utility "load"—blacked out—so that the rest of the system may be saved.

However, the FPC report cautioned, "Load-shedding should be regarded as an insurance program and should not be used as a substitute for adequate system design." In the wake of the 1965 blackout, Con Ed gave full measure to the load-shedding recommendation, but went only halfway on the recommendation to improve interconnections. Last July 13, starting in areas of Westchester, up to 50 per cent of Con Ed's load was automatically jettisoned, but still that was not enough. For Con Ed, at that point, load-shedding was putting a Band-Aid over the cancer. The preventive medicine had not been administered and the patient died.

Whenever Con Ed is accused of skating along the edge of its capacity, its officials say they want to provide the necessary reserves by building additional generating plants, but that they are blocked from doing so by environmentalists who object to construction of those plants. At a joint legislative hearing of the New York State Senate and Assembly held two days after the blackout, a Con Ed engineer testified that the utility, using its own generating capacity, could supply only 65 per cent of the city's peak demand. If Con Ed is indeed blocked from building additional generating plants, then the only way to meet the city's need is to build heavy transmission lines to import power from other systems in the area.

In its first interim report on the most recent disaster, the FPC called this blackout "clearly insupportable" and suggested it could have been avoided. It stressed the need for additional interconnections, and said: "The extreme vulnerability of New York City to a power failure . . . makes it all the more essential that the increased expenditures for improvement of reliability should be committed immediately."

In reply, Con Ed said, "In truth, the construction and operation of our system meet all the FPC criteria for such a system—as well as the criteria of every other regulatory agency to which we are responsible."

Despite the clear warning provided by the 1965 disaster, Con Ed's managers have not given high priority to large-capacity interconnections. Between 1965 and 1977 they took three steps to firm up the utility's ties to other systems. First, a line from Public Service Electric & Gas Co. in New Jersey to a Con Ed substation in Staten Island was increased from 138 kilovolts to 230 kilovolts. Next was the 500-kv link across the Hudson that tied in with the Pennsylvania-Jersey-Maryland pool and the New York Power Pool. The third, completed in December 1972, was a 345-kv cable from Public Service under the Hudson, across Manhattan, and under the East River to Brooklyn. That line was not in service the night of July 13—it had been down since September 1976, for repairs that will not be completed until next summer.

At the urging of Public Service Electric & Gas Co., Con Ed had been considering for years the construction of a heavy new tie across the Hudson. But in 1972, the company decided that such a tie would not be economical.

When I asked to talk to company officials or system engineers about why so few interconnections had been built, I was told that all of them were tied up with the company's board of review looking into the causes of the latest blackout. Arthur Hauspurg, Con Ed's president, told *The New York Times* that the company still envisioned expansions across the Hudson to be completed around 1982, although, he said, "we're looking at some alternatives to that."

To understand that kind of thinking, you must realize that Consolidated Edison is first of all a business, not a public service. Its executives are under pressure to maximize profits and provide substantial, regular dividends to its stockholders. The state utility commission sets a limit on the profit that can be earned, but it does not guarantee that the company will earn the maximum amount. Last year, thanks to rate increases that kept its electricity the costliest in the country, Con Ed netted $301,000,000, an increase of 55 per cent over the year before. Building heavy transmission lines for reliability costs millions of dollars, and that would cut into those profits.

But what if the lack of such lines practically guarantees that the system will fail from time to time? The cost accountants at Consolidated Edison and other private companies (and the banks that finance their bond issues) look at it this way: It may be more profitable, in the long run, *not* to spend the money for transmission lines that would ensure against blackouts. It may be less expensive for the power company to "accept" a blackout every ten or twelve years, factoring in the costs of getting the city back on the line as the normal costs of doing business.

Con Ed estimates the cost of restoring service after the recent blackout at $10 million. (The cost of damage claims will be covered by insurance.) The cost of the proposed PSE&G Hudson tie alone was estimated in 1975 at $97 million, with Con Ed to pay $38 million and Public Service $59 million.

A manager of the New York Power Pool, maintained chiefly by the seven major private companies in the state, put it this way: "If you had an infinite number of interconnections, you would never get into trouble. But how many of them is it worth the cost to build?"

Those questions would be answered differently by an executive of a private utility interested in making a buck and the owner of a store whose shelves had been stripped bare because the utility did not think it was essential to spend the extra buck to guarantee its service.

The cost of a blackout is more than the dollars the utility has to spend to get itself back in shape to begin earning its profit again. The cost, on July 13, was in danger to lives, in injuries to policemen, in loss of property, in anguish to thousands of disadvantaged families whose members thought they could get away with looting in the blackness but were caught in the act. The cost is in the tearing of the fabric of society.

But from a strictly business standpoint of company profit-and-loss, the cost accountants are correct. The costs of interconnections, after all, would have to be borne by the utility. Most costs of a blackout, on the other hand, will be borne by the city and its people. Mayor Abraham Beame estimated the cost of July 13 to the people of New York at hundreds of millions of dollars. Others estimated it at a billion.

It may be too much to ask an organization based on the profit motive to put the public interest ahead of its financial interest. But in the case of a monopoly on which the lives of the people depend, that may be exactly what has to be asked. Why should people who need electricity almost as they need their life's blood be required to pay a gratuity of 10 to 15 per cent to private shareholders who have little interest in ensuring their well-being? Given the high price the public has had to pay over the years for demonstrably unreliable service, Con Ed should be taken over by the New York State Power Authority and run as a nonprofit public service.

Meanwhile, the company may be directed by government to take the steps to guarantee reliability that it has been reluctant to take on its own.

Such a directive could come from the state's Public Service Commission, following the investigation ordered by Governor Hugh Carey. In time, directives to strengthen interconnections to ensure reliability may come from the Federal Government. The President's energy program, which, if approved, would become the National Energy Act of 1977, contains sections dealing with reliability of electrical utilities. The bill has been approved by the House, and is under consideration by the Senate.

The original language, written by George Hall of the White House Energy and Policy Planning staff, proposed that utilities set up stronger regional power pools than exist today. "We are for strong pools," Hall told me, "but we were only jawboning—there were no direct requirements written into the bill."

However, the House Commerce Committee decided the situation called for something stronger than jawboning. In place of the White House provisions on power it substituted language from a bill introduced by Representative John Dingell, Michigan Democrat, that would for the first time give the Power Commission authority to direct utilities to improve the reliability of their service. Under Part E, Title I of the amended bill, HR 6831, the FPC would be authorized to:

- Order utilities to construct interconnections where that is found to be in public interest.
- Where necessary, order Company B to "wheel" power over its transmission lines from Company A to Company C; Companies A and C would pay B for the costs of transferring the power.
- Investigate appropriate standards of reliability and set rules for companies and public power agencies to meet these standards.
- Require all utilities to come up with contingency plans for emergency situations and file these plans with the FPC.

Hall said the White House does not oppose the amendments; they would, in fact, make more certain the results the Energy staff would like to see. "In writing the bill," John Ahearne told me, "we wanted to extend interconnection beyond any local or regional areas." If the FPC were given authority to order interconnections between regional pools, it could move the country toward a de facto national power grid.

The energy staff members opted for weaker language, however, because they did not think provisions with teeth would get by without a fight with the private power companies. They were right; the fight has already begun.

As soon as the Dingell amendments were written into the House bill, the National Association of Electric Companies, the private utilities' lobby group in the Capital, sent a telegram to chief executives of its member companies calling them to a strategy council July 25 and 26 in Washington. It said:

"The House Committee has recommended legislation to subject the utilities and state regulatory commissions to detailed controls by the Federal bureaucracies. Power shortages, poor service, and increased costs to consumers will inevitably result. At the meeting we will discuss necessary communications with members of the House, Senate, Administration, the media, and the public to revise and overcome this proposed legislation."

I asked Robert Dolan, vice president of NAEC, why the private utilities were opposed to the reliability provisions.

"The real problem with this section," he said, "is that it would give the FPC authority over day-to-day operations of regional pools. It basically gives the FPC power to mandate interconnections and central dispatching of power. That makes sense in some areas, but not in others.

"Every company is trying day in and day out to improve the reliability of its plants. You can't pass a law setting standards of reliability to ensure reliability."

The private companies, he said, will try to convince Congress that the bill "will do them far more harm than good."

After the Northeast blackout of 1965, the companies responded to demands for increased interconnections by telling the Federal Government to keep out of it—they would do what was necessary by themselves, setting up "regional coordination areas." They established a National Electric Reliability Council, with twelve coordinating areas.

Companies in a specific area have long had informal pools to exchange power when it was to their mutual economic benefit to do so. Company A, for example, might have a peak demand at 12 noon, while Company B has its peak at 4 P.M. So Company A buys less costly off-peak power from Company B at noon and sells its off-peak power to Company B at 4 o'clock. These pools are all smaller than the utilities' regional coordinating areas, which could be the basis for regional grids for reliability as well as economy.

What some companies did after 1965 was augment transmission lines between the members of the economy pool to strengthen their backup for unusually high demand or for emergencies. This was done, for example, by the New England Power Pool, whose area was blacked out in the cascading failure of 1965.

In general, however, the companies' grid-building measures have been ad hoc. Their own statistics show no more than 50 per cent of the power is centrally dispatched by the pools or the regional coordinating areas. The New York Power Pool, of which Con Ed is a member, could not have routed electricity from its headquarters near Albany to meet the emergency in New York City. Con Ed was controlling its system on its own. Nor could the pool have arranged quickly to wheel power from the East Central Coordination Area in the Midwest across the P-J-M lines and into New York. A computerized national power grid could be engineered to make such adjustment in seconds.

Many public agencies and research groups that have studied the problem have come to the conclusion that a national electricity grid is not only feasible, but also essential. As a practical matter, such a grid could be set up only by the Federal Government. Congress could charter a public corporation to buy up the high-voltage transmission lines between systems and build them where they do not exist.

The public corporation would then tie the systems together into strong, centrally dispatched regional grids. These in turn would link into an integrated national grid that could wheel power from region to region, depending on the peak demand—or emergency demand—in a particular region. Different time zones and varying weather conditions make it a certainty that widely separate systems will have peak demands at different periods.

Private power companies and public power agencies would feed power into the grid and draw power from the grid. Costs of operating this backbone system would be assessed to each company or agency on the basis of its demand on the facilities and the pooled power it received. Each would be paid for the energy it contributed to the system.

In Sweden, the State Power Board has successfully operated such a grid, supplying the interchange requirements of both private companies and public power agencies since the 1920s.

White House energy staffers and people I talked to on legislative committees dealing with power agreed the country should move in that direction. But they are willing to settle for less because of the political and institutional problems that stand in the way.

"A national grid would alter the ownership arrangements of electrical utilities, and that's too tough a fight to take on at this time," was the way it was put by an administrative aide on the House

Commerce Committee staff. The private companies do not want to give up sovereignty over their interconnections even if that would strengthen their reliability and even if the Federal Government would pay the cost of these high-voltage links.

One corner of the power arena that has not been willing to settle for half consists of Senator Lee Metcalf, Montana Democrat, and his subcommittee staff director, Victor Reinemer. For a number of years, Senator Metcalf has been introducing bills that would bring about a national grid, only to see them shot down in the Senate Commerce Committee, which was not interested in taking on the power companies over those bills. Metcalf is now a member of the Senate Energy Committee, and next session he expects to introduce the bill through that committee, where he hopes to get a more sympathetic hearing.

"The movement for a national power grid comes alive for a few days after each blackout," Reinemer said, "but it seems to die as soon as the lights go back on."

In truth, a national grid will never come about unless a President becomes committed to the idea and pushes it hard as a national necessity. Carter might be that President, given his stated interest in exploring the possibility. He obviously wants the country to avoid having to suffer the consequences of other massive, cascading blackouts. The grid would be a reasonable guarantee against that. But what might lead President Carter to strong commitment is the argument that the grid has a built-in potential for enormous savings of energy: The least efficient plants in the country's power systems burn the greatest amount of oil and coal; with the national grid in operation, plants that waste fuel most would be brought on line last.

If the President gets behind the project and the grid becomes a reality, blackouts such as those of November 9, 1965, and July 13, 1977, will not longer be an American phenomenon.

THE UTILITY INDUSTRY—IV

(By Alvin Kaufman, et al.)

This selection discusses the pros and cons of integrating all utilities into a national grid, in which deficiencies in one area could be compensated for by margins in other areas. It concludes that reserves might be reduced 1 to 3 percent as a result of a strong national power grid without reduction of present standards of reliability.

THE NATIONAL ELECTRICAL GRID—A CONCEPT WHOSE TIME HAS COME?

(By Alvin Kaufman, Barbara M. Daly, Gary J. Pagliano, and Russell J. Profozich—May 2, 1978)

INTRODUCTION

The concept of a national electrical grid has been debated for some years, at least since the first National Power Survey in 1964. In that document, the FPC indicated the benefits of a national interconnected system might well outweigh the costs. In the intervening years, some steps have been undertaken to institute the concept, and at the moment bills have been introduced in Congress (S. 1991 and H.R. 8793) to implement the system. As a consequence, we have undertaken to prepare this discussion of the national grid concept.

THE INDUSTRY

The ownership of the electric utility industry is split between investor (privately) owned and publicly owned utilities, with 75 percent of capacity being investor-owned. Despite this preponderance of privately-owned capacity, the bulk of the utilities are publicly owned. Most of the latter are distributors only. The larger public and private systems, however, tend to be vertically integrated.

Traditionally, the industry is broken into three segments: production or generation, transmission, and distribution. The national grid concept involves for the most part, connecting the transmission of the various utilities into a single system.

Transmission is usually considered as lines over 69 kilovolts (Kv) with the bulk supply system regarded in excess of 230 Kv. As of June 30, 1976, there were 120,500 miles of bulk power transmission in the United States; a year earlier the system totaled 117,000 miles. In addition to transmission within the United States, there are interconnections with Canada and Mexico. In 1975, the United States imported 15.4 billion kilowatt-hours (Kwh) from Canada. In the case of Mexico we exported a net 428.2 million Kwh. We, thus, are a net importer from Canada and a net exporter to Mexico. It is anticipated that there will be four major new interconnections between the United States and Canada between now and 1984. One of these will be at 765 kilovolts and will be the highest voltage international transmission line in the world. The line will connect James Bay in Canada with New York City. We, thus, apparently intend to increase our dependence on the Canadians for electric energy in the future.

By 1984, it is expected that we will add 61,000 miles to the present major supply transmission network, with two-thirds of this addition at the 230- and 345-kv levels. The highest presently operating alternating current transmission voltage is 765 kv with 1,500 additional miles proposed at that level by 1984. In addition, it is anticipated that 1,844 miles of direct current line will be in service by 1984.[1]

SOME CONSIDERATIONS REGARDING INTERCONNECTION

The national grid, as noted earlier, involves the interconnection of the utility systems in the United States. To accomplish this, however, involves consideration of the technologic and environmental constraints. These are discussed below.

Technologic considerations.[2]—From the 1920's through the 1970's, there were a series of design improvements in transmission voltage levels which resulted in increased capacity, better reliability and longer transmission distance capability. These developments, however, occurred primarily because transmission development is conditioned by the needs of generation. The timing of pioneer work in transmission reflects the anticipated demand for high capacity and long-distance circuits to carry what has been produced in the generating plant. The steady increase in voltage levels has allowed the economic movement of large blocks of energy over relatively long distances. A side effect is the change in the number and structure of investor-owned utilities. Many are merging, are getting out of the generating and transmission business and purchasing from others, or joining generating and transmission cooperatives. The increase in size and expense of plants is forcing more and more small utilities, regardless of ownership, to become distributors only. This, of course, indicates an expanded need for more and more transmission as time goes on.

Utilities now spend approximately $7 billion a year to upgrade and expand their power transmission systems. Overhead transmission is still the most economical and efficient means of moving large blocks of power. This means that the utilities must compete for land with other users, since some 15 to 20 acres are required per mile of transmission line. As a consequence of this competition for surface area utilities have moved to higher voltages to reduce land presssure and to accommodate bigger generating units. In the 1960's, lines at 345 and 500 kv were introduced. Today there are a few lines operating at the 765-kv level, with efforts underway to bring on an economical 1,200-kv transmission line. This work is being sponsored by the Electric Power Research Institute (EPRI). Among the questions that need to be answered is the effect on biological systems of electrical fields at the 765-kv level and up. Further, work is underway to handle other environmental issues, such as audible noise, interference with radio and TV, etc.

In addition to this ultra high voltage alternating current transmission, high voltage direct current (DC) transmission is also being investigated. This concept began in Sweden some twenty years ago, and appears useful for long distance, point to point, bulk power transfer. The first U.S. installation was commissioned in 1970 as the intertie between the Columbia River hydro facilities and Los Angeles.

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[1] Federal Power Commission Annual Report, 1975 and 1976.

[2] The material above was derived from the following: A. "EPRI Journal," Electric Power Research Institute, January/February, 1977, Volume 2, No. 1, pp. 34–43. B. Hughes, William R. "Scale Frontiers in Electric Power," Chapter in Technological Change in Regulated Industries. W. M. Capron, editor, The Brookings Institution, Washington, D.C., 1971, pp. 44–85. C. Breyer, Stephen G. and Paul W. Macavoy. "Energy Regulation by the Federal Power Commission," The Brookings Institution, Washington, D.C., 1974, pp. 90–121.

Before the DC concept can become widespread, a compact, direct current converter station is required. Two 100-MW demonstration terminals, plus a DC link, are under construction at Astoria in New York City, by Consolidated Edison under the sponsorship of the Electric Power Research Institute (EPRI). This work, if successful, will prove the DC technology up to the 400 kv level. The units should be ready for testing and evaluation in early 1978. It is hoped that a compact DC converter station will be commercially available by the early 1980's.

The pressure on land has also put pressure on transmission planners to put lines underground. Distribution has typically been undergrounded in some residential and urban areas to improve esthetics. Transmission, on the other hand, has been underground only in areas where corridors were not otherwise available due to high cost and technical problems. Work is now underway to change the economic and technical factors for undergrounding from unfavorable to favorable. The major problem appears to be the need to keep cables relatively cool under high voltages and thus avoid a heat buildup with a possible faulting of the cable.

Environmental considerations.—The physiological effects of high voltage transmission lines have caused some concern. In 1975, the New York Public Service Commision (PSC) held hearings on the health and safety aspects of a 765-kv transmission line proposed by Rochester Gas and Electric and Niagara Mohawk Power Corporation. Central to the case was the effect on human beings of electric and magnetic fields caused by high voltage transmission lines. The case resulted in rules which will affect all transmission certification cases in New York State and could set the standard elsewhere in the country. In its decision the PSC said high voltage lines must have such added protection as an extra 200 feet of right-of-way near human housing and 48 foot clearance over highways. Utilities must also launch education campaigns to warn residents of potential hazards. The rules, some experts say, could add 10 to 15 per cent to the cost of high-voltage lines in rural areas. The additional right-of-way requirement may make 765-kv lines prohibitively expensive in urban locations

Turning from health and safety to ecology, we note that there is environmental concern about developing additional large generating centers in the western coal areas. In the Four Corners area (the junction of the States of New Mexico, Arizona, Utah, and Colorado) large scale coal fired power plants were built in the early 1970's, with more planned. Construction of planned plants has been delayed primarily because of the environmental complications caused by power plants. Emissions of existing plants have measurably degraded air quality in the region. Even with installation of the best pollution control technology, development of additional plants will probably result in further air quality degradation.

The planned power plants are also potentially large consumers of scarce uncommitted water supplies of the arid portions in the West and Southwest. The decisions to preempt this water for power plants to the exclusion of alternative uses are under review by the appropriate branches of the Federal and State governments.

In Montana, which has part of the Northern Great Plains coal resources estimated at 1,518 billion tons, environmental concerns have blocked rapid and uncontrolled development of coal resources. Montana has enacted a power plant siting certification process which requires a thorough environmental impact study including among other things, land use, water resources, and air quality impact. An application for certification will take at least 2 years to process before power plant construction can begin, mainly because a number of State government agencies and Federal air and water quality agencies must study the proposal before a decision is reached.

The situations in Montana, Four Corners and New York demonstrate that environmental considerations represent significant probable delays to any serious plan to complete a national grid in the near future. The environmental considerations will mean higher project costs and add to the already long lead time necessary for the planning and construction of such ventures.

THE NATIONAL GRID SYSTEM

Utilities undertake interconnections for two major purposes. In the one case, interconnections are undertaken to improve the reliability of the system, and to provide an emergency source of energy. In the second case interconnection is undertaken in order to obtain operating and investment economies through the integration of the systems (central or economic dispatch).

The current situation.—The majority of interconnections in the United States are for reliability purposes. To accomplish this there are nine regional councils which constitute the National Electric Reliability Council. These help in coordinating systems planning to assure improved reliability. The result of such efforts has been the creation of three major transmission networks: one each in the East, West, and in Texas. The utilities and pools in each network are intertied with each other, but the three networks are not connected. The networks are designed to improve planning and reliability, but do not employ central dispatch.

The pools included in this group include the California Power Pool, the Central Area Coordinating Group, the Eastern-Missouri River Basin Power System, the Eastern Wisconsin Pool, the Florida Consulting Group, the Illinois-Missouri Pool, Mid-American Planning, Pacific Northwest Pool and the Rocky Moutain Power Pool. The main thrust of these groups is in coordinating the planning of new capacity, in load frequency control, in the development of emergency procedures and in coordinating maintenance scheduling. These activities make the coordinated network feasible and reliable. This in turn can lead to economies of scale in equipment components and through the pooling of reserves.

Aside from the above, there are utility groups interconnected and employing central dispatch, The latter involves operation of generating units based on optimum economic operation for the interconnected system as a whole, rather than operation based on availability of an individual utility system, The centrally dispatched systems tend to be located in the East, and comprise approximately 38 percent of U.S. generating capacity. Some are under the financial control of a single entity (holding companies), and some are voluntary associations of independent utilities. Among the independent groupings are the Pennsylvania-New Jersey-Maryland Power Pool; the New England Power Pool; the New York Power Pool; the Michigan Coordinated System; and the Michigan Municipal Cooperative Power Pool. The company groups include the Allegheny Pool Systems; the American Electric Power System; Commonwealth Edison and Central Illinois; the Southern Company; Tennessee Valley Authority; and Middle South Utilities.

The National grid system—pros and cons.—The creation of a national grid generally would involve the interconnection of virtually all of the electrical generating capacity of the nation into what could be a single power supply system.

The proponents of a national power grid contend that such a system would achieve economies not otherwise available by taking advantage of the load diversity not already being utilized by existing interconnected systems. Load diversity derives from the fact that maximum demand occurs on individual systems during varying times of the day and seasons of the year. Intercontinental systems can take advantage of this diversity by sharing the capacity available on the individual but intertied systems. This would lead to economies of operation since base load generation, which generally has the lowest operating cost, can be used a greater portion of the time than would be the case without system interconnection. The greater plant utilitzation then permits the high capital costs of these units to be spread over more output. As a consequence, overall costs are reduced.

Other benefits available through system interconnection include economies of scale, reduction in the need for generating reserves; and improved reliability. The economies of scale occur because, as a general rule of thumb, it is less expensive on a per unit basis to build a larger generating plant or a larger capacity (higher voltage) transmission line. The scale economies will eventually tail-off. For example, transmission costs may more than balance the generating savings as the interconnected system becomes larger, and management costs may increase substantially as the complexity of the system increases. Interconnection, however, can allow, construction of larger generating units than might be economically justifiable on the individual systems so that economies of scale can be realized. Participants will derive increased efficiency and lower operating costs compared with the installation of individual smaller units on each system.

An interconnected system can reduce generating reserve requirements by coordination of maintenance schedules among the participants, so that each utility can cover for the others when equipment is out of service. Further, since it is unlikely that several units will suffer forced outages at the same time on the various systems, lower reserves can be carried within a utility by depending on the other members of the interconnected system for emergency capacity. Thus, the national grid tends to improve the reliability of the total system by enabling available reserves to be more effectively utilized throughout the combined areas of the utilities at all times.

The opponents of a national power grid argue that the economies attributable to expanded system interconnection are illusionary.

They contend that those economies of scale and operation which are available through system interties have already been achieved through present-day interconnections (both existing and planned). These interties have been initiated through voluntary cooperation—and Federal and State encouragement—of publicly and privately owned electric utilities. Further economies are simply not available due to the erratic nature and uncertain magnitude of the remaining load diversity.

Those opposed to a national power grid also point to the increased involvement of electric utilities and regulatory commissions in time-of-day pricing and load management techniques as another factor limiting the usefulness of the national grid proposal. These methods of demand modification are designed to improve system load factor and equipment utilization. As such they would reduce further the economies available through system interconnection.

Other issues to consider, are the effects of a national power grid system on the structure of the electric utility industry and on the methods of regulating that industry. Opponents of the national grid proposal argue that the proposal would cause the vertical disintegration of the electric utility industry, and that separate ownership of generating, transmission and distribution facilities would adversely affect the perception of risk on the part of the investors and hamper system expansion and coordination by making it difficult to raise money.

In regard to electric utility industry regulation, the national power grid proposal raises the question of which regulatory commission(s) would have jurisdiction over the operations of a national power grid corporation and the associated and interconnected regional bulk power supply corporations.

Current regulatory procedures are mostly a State matter, with only about 20 percent of industry sales regulated by the Federal Government.[3] The regional corporations established through the national power grid, however, would cross State lines and thus would pose a jurisdictional problem. Would these corporations be subject to regulation by the various States in which they operate, by a new hybrid regulatory agency made up of representatives from the various States, or by a Federal agency?

The feasibility of a national grid.—Some of the questions and issues raised above were answered in a 1975 study prepared for the Congressional Research service at the request of the Senate Committee on Interior and Insular Affairs.[4] The study, through analysis of previous research and existing data and material, examined the economic, regulatory, and engineering aspects of the various issues relating to the creation of a national power grid. Through this examination of "the state of the art" the study concluded that:

(*a*) There is very little usable load diversity among electric systems that is not already being utilized by existing interconnected systems. Diversity across time zones is too small, erratic in magnitude, and uncertain as to time of availability to be useful in planning generation capacity reductions. Nationally, load diversity as a percentage of the annual peak load is not likely to increase in the future.

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[3] Interstate sales of electric power and sales for resale.

[4] See: National Power Grid System Study—An Overview of Economic, Regulatory, and Engineering Aspects, a study prepared by the Congressional Research Service for the Subcommittee on Minerals, Materials and Fuels of the Committee on Interior and Insular Affairs, U.S. Senate, U.S. Government Printing Office, Committee Print.

(*b*) Most utilities are now receiving substantial benefits in the form of lower reserve requirements as a result of interconnection and coordinated operations. While a definitive study of reserve requirements of a national grid is not available, analysis of existing studies suggests that reserves might be reduced 1 to 3 percent as a result of a strong national power grid without reduction of present standards of reliability. Significant reductions could be made in the amount of installed generation capacity if overall electrical system reliability levels are reduced.

(*c*) Electric utility systems in the Eastern, Midwestern and Southern portions of the United States are now effectively interconnected and their operations coordinated to obtain a large measure of pooling benefits. With the exception of the Far West and Texas systems, the electric utility systems in the contiguous States will be, for practical purposes, fully interconnected within the next decade. With foreseeable technology, a nationwide extra-high voltage grid superimposed on the existing transmission systems would be very costly and in other aspects less attractive than the transmission network that is currently evolving.

(*d*) Effective interconnection between the now separately operating systems of the Far West and the Midwest would be advantageous if one or more large power generating centers were developed in the coal-rich West to serve loads in both regions. The benefits of additional Pacific Northwest-Pacific Southwest interties, and interconnections between the Midwest United States and Canada should also be analyzed.

(*e*) A Federal Power Commission study in 1972 found that there would be a net economic benefit to an interconnection between the Electric Reliability Council of Texas interconnected systems and the interconnected systems of the Southwest Power Pool.

(*f*) Increasing interconnection and power pooling activity of electric tuilities indicates a need for regulation based on a broader jurisdiction than a single State. Regional regulatory agencies, or strengthened Federal regulatory authority, for regional and multiregional utility operations should be explored. However, important regional differences influencing power system characteristics must be respected in the consideration of regulatory restructuring.

The above conclusions are not at all clearcut, and hinge on one's perception of the costs and benefits.

Costs and benefits.—There is very little data available in regard to the savings that accrue as a consequence of interconnection. Such savings will vary from system to system, and should be computed on a system by system basis. Some indication of savings, however, may be derived from the materials prepared in regard to the Texas intertie situation.[5]

In 1972, the FPC indicated that a decreased generating reserve requirement, and consequent savings in investment, would result from an intertie between the Texas utilities and the Southwest Power Pool. They estimated the annual generating cost savings would be $193 million in the 1975–80 period, discounted at 8.4 percent per year, but that this would be offset by increased transmission costs resulting in a net present value savings of $156 million. These numbers are somewhat out of date since a generating unit investment of only $90 per kilowatt was used. Further, that study only covered benefits from reduced reserve requirements.[6]

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[5] See: "The Electric Reliability Council of Texas Intertie Situation," a study by the Congressional Research Service for the Subcommittee on Minerals Materials, and Fuels of the Committee on Interior and Insular Affairs, U.S. Senate. Government Printing Office, Washington, D.C., 1976, 30 pp.

At the time, the major regional generation consisted of small units fueled by inexpensive natural gas and located close to the consuming area. This may well have made an interchange arrangement economically infeasible. With the move in recent years toward large nuclear or coal-fired plants, there is presently a somewhat different situation. In 1975 Power Technology, Inc. prepared a study for the Central and Southwest Corporation electric power system. The base plan in that study assumed a mixture of new nuclear and coal units with reserves installed locally, and indicated that revenue requirements through 1995, assuming no interties outside of Texas, would have a present value of $8.9 billion compared with $8.7 billion assuming interties with the Southwest Power Pool. Thus consumers could save approximately 2 percent if the Central and Southwest Corporation intertied its various utilities to each other and to the other Texas systems. If they operated without ties to the other Texas systems, the present value of revenue requirements would rise by some 1 percent.

The least costly plan developed by Power Technology, Inc. assumed a mixture of large coal and nuclear units dispersed throughout the Central and Southwest territory, 15 percent reserves for the system, and interties both within Texas and to the Southwest Power Pool. In this case the present value of revenue requirements would be $8.5 billion, or 4.5 percent less than the non-intertied base case.

The study concludes that interties would result in long run economies, but these savings were only computed for Central and Southwest. Thus, possible benefits and costs to the other systems are not included. Considering that regional interconnection generally results in greater use of the more efficient generating units and in this case will result in shorter transmission lines, the benefits to Texas of intertieing may be much larger than those for Central and Southwest Corporation alone.[7]

In any case, the available information indicates that strong interconnection between utilities may result in 2–3 percent savings for the consumer.

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[6] Bureau of Power, "Study of Proposed Interconnection Between Electric Reliability Council of Texas (ERCOT) and Southwest Power Pool (SWPP), FPC, Fort Worth, July 1972, p. 26.

[7] Wood, A. J. and C. A. Mac Arthur, "Expansion Study of the Central and Southwest Corporation Electric Power System," Power Technologies Inc. Nov. 14, 1975, p. 11.

THE UTILITY INDUSTRY—V

(By the Electric Power Research Institute)

This article from the EPRI Journal describes a model, developed by the electric industry research group, to help utilities decide how much capacity to build, in the light of uncertainties about future load growth and other factors. The article is useful in detailing the difficulties currently facing utilities in planning for the future. Perhaps most interesting is the model's attempt to quantify the costs of power outages—and its assumption that environmental costs will be the same regardless of the amount of reserve capacity that a system builds.

[From EPRI Journal—May 1978]

Planning for Uncertainty

Reserve generating capacity costs money, and so does a capacity shortfall. But as future electricity demand becomes harder to forecast, larger planning reserve margins may be more economical in overall cost to consumers.

When I was put in charge of load forecasting at Commonwealth Edison a number of years ago, some people considered it the easiest job in the company," reminisces René Malès, director of EPRI's Energy Analysis and Environment Division. " 'Growth is so regular in this industry,' the chairman told me, 'in a 10-year period you can't be wrong by more than one year—either too early or too late. We can take care of that in the construction department. So, instead of doing a complex analysis, you could just as well take a ruler and draw a line and be right plus or minus a year.' "

In those days steady demand growth and short construction lead times meant that the various departments in a utility could depend on a load forecast without concern that it would be changed. The load forecaster gave his projections to the operations planner, whose time was mainly spent on immediate capacity additions rather than on system plans for a future 10 or 15 years down the road. Fuel supply and sound financing were regarded as assured "givens" by planners, and the environmental impacts of electric power production had not yet become a social issue.

A CATALOG OF UNCERTAINTY

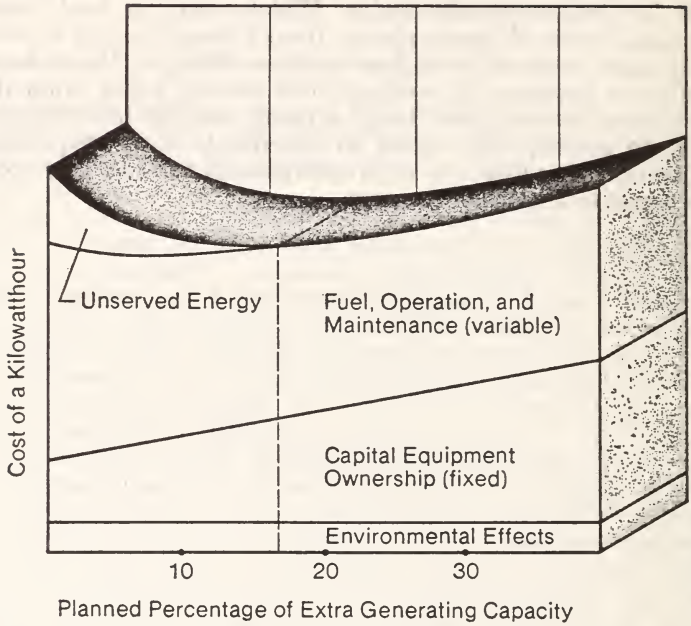
Today, load forecasting is no longer easy, and the job of planning a utility's capacity expansion has become a task requiring complex coordination of many departments. Systems planning is now distinct from operations planning; fuel supply forecasting is a crucial and uncertain factor; the financing of multimillion-dollar power plants with lead times up to 12 years—or even more—is a major undertaking; and environmental concerns have become a highly sensitive issue.

The largest single difficulty in making wise capacity expansion decisions is that the future demand for electricity is much more uncertain. No one knows what effect higher fuel prices and changes in rate design will have on that demand. Technological changes—industrial cogeneration, heat pumps, solar heating and cooling systems—will have their influence, but their form and extent are difficult to foresee. Government decisions like California's tax incentive legislation to encourage homeowners to install solar systems or the proposed federal tax incentive for conservation may also alter demand—though it is still uncertain if or when the federal legislation will come about. Further, no one is sure what level of economic growth the country will realize over the next 10–15 years.

No one knows what combined effect all these factors will have on the kilowatts of plant capacity that must be planned. The forecaster's computer can juggle figures forever, but it can't create certainty about future demand when none exists.

A second difficulty in capacity planning is inherent in today's technologies for generating electricity. Widely varying lead times control the installation of power plants, from 2 years for gas turbine systems to 12 years or more for nuclear facilities. Bringing these plants on-line involves a sequence of decisions over several years, from the initial commitment to study and design a plant, through licensing and construction, to startup. The need to coordinate these sequential decisions with changing forecasts of future demand considerably complicates the capacity expansion process.

The Cost of Future Reserve Capacity



Every electric utility has generating units standing in reserve (over and above nominal system requirements) to deal with extraordinary peak loads and to substitute for units that break down or must be shut down for periodic overhaul. All units on a system must be planned well in advance, requiring orderly commitments of money and time for studies, designs, licenses, and construction.

When future demand is uncertain, the amount of future reserve margin to have in the various stages of commitment and investment is a complex planning question. But there are foreseeable cost penalties that will result from arriving at a given future date with either too much or too little reserve.

This U-shaped curve represents the output of a method devised by EPRI to compare the costs of different planning reserve margins on a utility system when probabilities are assigned to various future values of system capacity requirement. The low point marks the future margin of least overall cost as it is seen today. Equally important are the slopes of the curve away from the low point; these indicate that electricity cost is apt to increase more sharply with a lower reserve margin than with a higher margin. The costs of unserved energy—incurred by consumers during a blackout, for example—are not on electric bills but the assigned level of these outage costs is crucial to the analytic method.

A DIVERGENCE OF VIEWPOINTS

Even if demand were certain and decisions could be closely coordinated, a tough issue would still remain. Energy planning decisions involve many parties outside the utility itself, all with their own interests and viewpoints, and no agreement exists about what the ultimate goals should be or how one set of values can be traded off against a different set. On the one hand, a large utility customer—a computer center—wants to be sure its service is totally reliable because just a few seconds of interrupted service could erase its data base. On the other hand, a public interest group may question the value of capacity expansion, especially if it involves construction of a nuclear plant. Or a state commission may want to control expansion by limiting the number of sites it will approve for utility use.

The implications of these various, often conflicting, views are usually measured on different scales, and the lack of a common language has made the resolution of such differences a frustrating problem to everyone concerned.

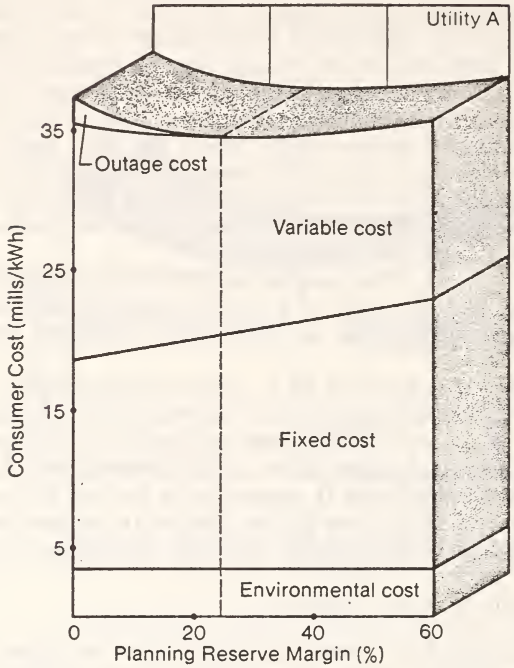
In view of all these factors, the position of a utility planner today is akin to that of a traveler facing a fog-shrouded highway. Will there be a clear, straight stretch ahead, without curves or obstacles? More likely there will be forks in the road, alternative routes among which to choose. And what about the vehicle—is it appropriate for the route ahead, or will it slow him down? Will there be the chance to exchange it for equipment better matched to the terrain actually encountered?

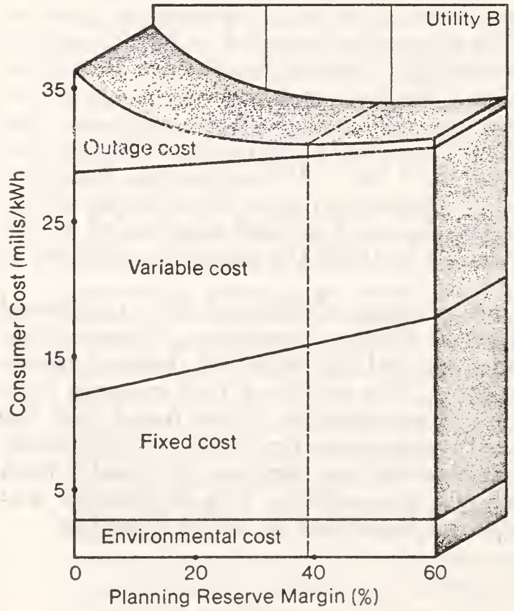
CALL FOR A NEW QUESTION

Similarly, the planning process has entered an era of new complexity, where down-the-road visibility is obscure. Up to now, utility capacity expansion plans have been based on the expedient question, What is the future demand for electricity expected to be? To answer that question, elaborate econometric models have been developed that extrapolate the future from the past and present. Aware of uncertainty in the future, planners usually produce high-, medium-, and low-demand scenarios and then choose a compromise figure that reflects an implicit hedging of their bets. Although some flexibility results from this approach, the information used to arrive at expansion decisions and determine the desired flexibility gets buried within the total data, and it isn't possible to track the reasoning involved in the decision making.

Recently a small group of analysts challenged this traditional approach In 1976 the California Energy Resources, Conservation, and Development Commission studied the effect of demand uncertainty on optimal expansion rates. The results of that research were unexpected. With the addition of uncertainty, it was found that the most beneficial rate of capacity expansion (in terms of minimizing possible additional costs to consumers) was significantly greater than the expansion rate when demand was certain. The implication was that demand uncertainty is indeed important in utility planning.

The Optimal Planning Reserve Margin





Different circumstances among individual utilities—notably the mix of planned types of units and the cost assumptions for outages (unserved energy)—influence the shape of the U-shaped curve and the optimal reserve margin that results, which is measured as the levelized consumer cost of electricity required to achieve that margin.

The optimal 24% margin of hypothetical Utility A, for example, is controlled by the fixed and variable costs of units that it would add to attain various reserve margins. This circumstance can result from a heavy proportion of oil-fired capacity today. Replacing some of it over time with coal-fired or nuclear units will yield lower variable costs (fuel and O&M) Outage costs are a small increment in this example because Utility A's hydroelectric capacity is substantial and is thus a reliable, flexible, and economical source of peak demand power.

Utility B, on the other hand, has a large proportion of efficient baseload capacity that results in low variable costs. Capacity additions can only increase its fixed costs, even though variable costs taper a bit. Furthermore, on this system of large units, even one forced outage implies more unserved energy and sharply greater outage costs if the future reserve margin falls short. This drives Utility B's optimal planning reserve margin to nearly 40%

In view of this finding, it appears that a new question for planners is in order. Rather than asking what demand will be, a better question is, What is the best way to plan capacity expansion based on demand uncertainty? In other words, knowing that the road ahead is hidden by fog, the best way to prepare for the junctions and forks that may lie ahead is to make uncertainty an explicit part of the decision-making process.

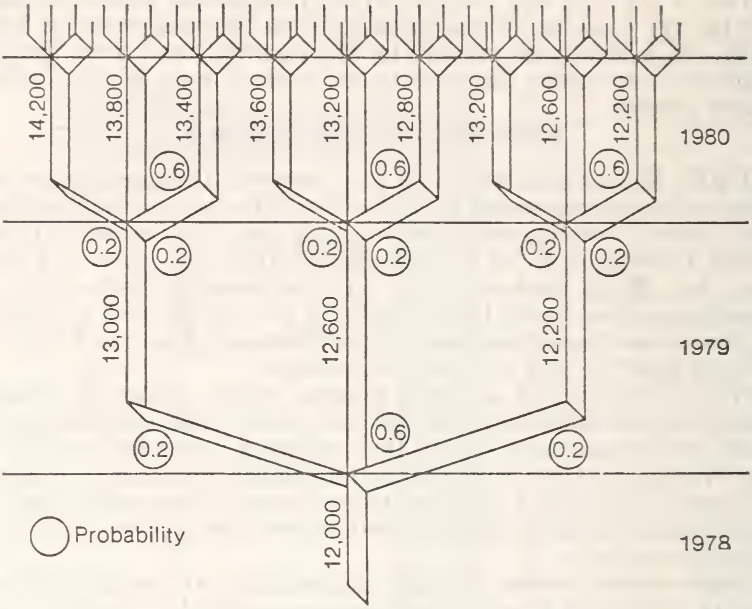
RESPONDING TO THE QUESTION

EPRI's Energy Analysis and Environment Division has recently developed a planning model to deal with utility decision making against many futures. Starting with methodology that they helped to develop at SRI International for the California study, analysts of Decision Focus, Inc. (DFI) worked closely with the planning staffs of four participating utilities (Long Island Lighting Co., Pacific Gas and Electric Co., Tennessee Valley Authority, and Wisconsin Electric Power Co.) to ensure that the new approach is relevant.

"We were interested in really locking minds, using the practical methodology of the utility planners and the decision analysis expertise of DFI to synthesize something that can work in the real world," says Jerry Karaganis, the Systems Program project manager who directed the study. "The utility planners helped develop the model itself, and the net result was a significant advance over the approach used in the California study."

EPRI's model makes demand uncertainty an explicit factor in capacity expansion planning and uses it to build a flexible electric power system—that is, one for which a utility can make cost-effective decisions about capacity additions as demand actually materializes. The results of EPRI's analysis suggest that such a flexible system should actually cost consumers less money than would a conventionally optimized planning procedure.

A Picture of Probabilities



The uncertainty of system capacity growth requirements is represented by this probability tree of alternatives for the next two years. Extended and branched throughout a planning period, it produces a range of future capacities and reserve margins. With recognition of generation types, costs, and lead times, that range can be reduced to a present-day estimate of the future mix that must be committed to successive planning, licensing, and construction stages during the intervening years. Revised demand forecasts and probabilities can be incorporated annually (and the plan extended another year) so as to accelerate or slip the scheduling of future units

FOUR COST COMPONENTS

As a basis for its analytic and modeling approach, EPRI suggests that the costs associated with producing electricity and providing service be divided into four categories: fixed, variable, outage, and environmental costs—all of which the consumer ultimately pays, directly or indirectly. Fixed costs are represented as carrying charges on capital investments. Variable costs are those of fuel, of labor and parts associated with maintenance, and of meeting demand by turning to interties, interruptible customers, and voltage reductions.

Customers not only pay for electric power, they pay for not receiving service as well. Thus, the cost of outages, or unserved energy, is a crucial component of this approach. Analysts are only beginning to devise methods of attaching dollar values to the costs associated with interruption of utility service. It is clear, though, that these will always be specific to each utility and that they will change over time as the utility's service area changes and matures.

Basically at issue is how much the utility's customers value reliable electric power. If, because of service interruptions, customers install their own emergency generators, they incur real, calculable costs above those that appear on their utility bills. Or instead, if perishable merchandise spoils or customers lose business, they also incur real costs.

Outage costs, then, are a societal cost that should be included when a utility attempts to plan a least-cost system for its customers.

All utility planners today place a value on outages for their planning purposes. EPRI's contribution to the issue lies in the way in which it makes outage costs explicit in the decision-making process. It enables utility personnel to run a sensitivity analysis to reveal if their planning decisions would change if they placed a different value on outage costs.

Finally, environmental costs are associated with electric power generation. On the one hand, an undersized, older utility system contains generating units that are being pushed past their optimal efficiency. As a result environmental controls are not as effective as planned, and the company may need to seek variances or pay fines for airborne particulates that pollute the air. On the other hand, a system with planned overcapacity can schedule proper maintenance and run its units efficiently, so that it tends to be environmentally sound. In this regard, it is important to remember that an oversized system does not necessarily produce more energy than an undersized system, and where energy production is the same, the total amount of pollutants released would actually be less with the oversized system.

There is still another trade-off to consider, since planned overcapacity ties up land. This does not mean that power plants are sitting around unused. Rather, sites may have been approved and plants licensed that are being held in that status, or "slipped," until demand or other issues are resolved and the plants are either built or cancelled. In EPRI's study, a balanced trade-off in environmental costs between under- and over-sized systems was assumed, according to the present state of knowledge about the issues. In other words, environmental costs were held constant.

FOCUS ON RESERVE

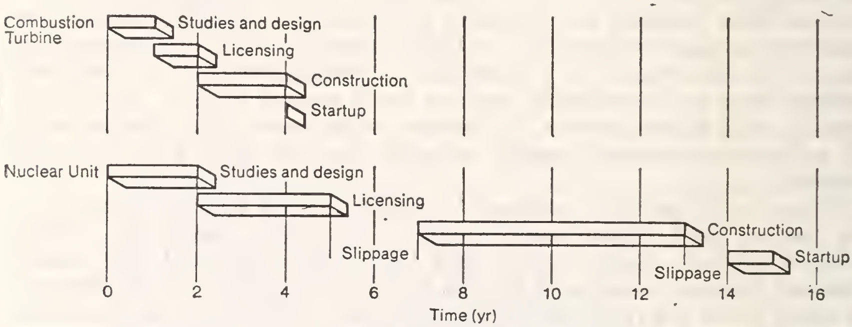
For purposes of this analysis, the planning reserve margin was made the decision variable. This is a measure of reliability that is easier to conceptualize than is the traditional utility measure, loss-of-load probability, which is expressed in terms of the number of outage days in a certain number of years.

When a utility feeds data relating to the four costs (fixed, variable, outage, and environmental) into the capacity expansion model, the model attempts to represent electric capacity additions for that utility, guided, of course, by several givens: a mix of generation technologies, a planning reserve margin, and a demand probability tree. The tree simulates the multiple futures assumed for electricity demand. Consisting of several branches and nodes, it represents the fact that in each particular time period demand may turn out to be high, medium, or low. The branching pathways capture the fact that the expectation of demand growth becomes increasingly uncertain as one looks further into the future. The uncertainty associated with each pathway can be handled probabilistically. As a result, each branch at each node is labeled with a certain probability of occurrence.

SIMULATING GENERATION EXPANSION

As the model moves through the planning period, it makes decisions on how the system should expand, based on how demand uncertainty gradually resolves, what consequent future demand becomes evident, what initial capacity was available, what generation mix is desired, and what lead times control various new capacity additions. The model simulates the sequential decisions that utilities must make to carry planned additions from initial studies through licensing to actual construction and startup. Procedures allowing plants to slip at any stage of the process are an important way that utilities deal with demand that changes after an initial commitment to a capacity addition. In this way the fixed costs of an expansion plan can be computed.

The Timing of Capacity Additions



Each type of generation unit—a combustion turbine for peak demand service or a nuclear-powered baseload unit—has its own time scale for each stage of development until it comes on-line. (These increments vary from one utility to another.) If the demand forecast falls off, the unit can be slipped; if demand picks up, it can be replaced in the plan by a different type of unit having a shorter lead time (with a consequent change in the cost picture).

The model simulates electricity production and computes the variable costs for each year of the planning period along each pathway of the probability tree. When these fixed and variable costs are added to the calculated outage and environmental costs, the result is a stream of total costs for each pathway. These costs are then discounted back to 1978 dollars, a procedure that determines their present value to consumers. Next, the model levelizes each pathway's cost to consumers over the planning period. Finally, using the probability associated with each pathway, the model computes the expected cost to consumers of the expansion plan at a given planning reserve margin.

VARYING THE RESERVE MARGIN

When the model runs several times, each time with a different planning reserve margin, curves associated with the four cost categories are produced.

As would be expected, fixed costs increase steadily as the planning reserve margin increases, since more capacity is being installed. On the other hand, variable costs tend to decrease with added capacity since utilities can replace older technologies or oil-fired plants that have become expensive to operate with a new and more economical mix. Outage costs decrease with increasing reserve margin because a utility with greater reserve can meet more of the demand for power. Environmental costs are shown by a horizontal line indicating that a constant value is assumed. If actual figures are available to a utility, they could be used in sensitivity analyses in the same way outage costs are.

A SIGNIFICANT CURVE

The results of this new type of analysis are significant. When the fixed, variable, and outage costs are fitted together, a curve emerges whose shape is not only U-shaped but also asymmetrical. The bottom of the curve locates the least-cost planning reserve margin when demand is uncertain. The cost to consumers of electric power is minimized when capacity expansion is pegged at that reserve margin.

The curve's asymmetry shows that the additional costs associated with planning at a lower reserve margin (and consequently sometimes ending up with undercapacity) are significantly larger than the costs associated with planning at a higher reserve margin and its potential for overcapacity. In other words, if a utility maintains a low planning reserve margin and demand turns out to be consistently higher over time than was anticipated, the utility must attempt to meet that demand by installing modes of generation with short lead times (which tend to use expensive fuel), drawing on interties, interrupting service, or even incurring outages. The costs to consumers of these eventualities are greater than the costs of supporting a higher planning reserve margin, even though it entails the commitment to studies, licensing, cor onstruction of generating units not actually needed if demand turns out to be less than expected.

INFORMATION SENSITIVITY

The U-shaped curve actually represents a best-guess case and is really only the starting point in a debate over a utility's capacity expansion plans. Its value lies in pinpointing the critical information for a specific utility. By using sensitivity analyses, various views can be accommodated to determine how a change in one assumption might affect the utility's expansion planning decisions.

For example, how would the curve look if outage costs double? A sensitivity analysis might indicate that the least-cost planning reserve margin would shift 10 points to the right under those conditions. Or conversely, it might reveal that the particular utility is not sensitive to changes in outage costs. If it relied heavily on one generating technology, however, the analysis might show it to be quite sensitive to an increase in the cost of oil or to a coal strike. In other words, the model is sensitive to the specific information brought to the debate. As a result, the parties involved can determine which arguments are actually pertinent and which ones only cloud the issue.

Karaganis recognizes that the particular model developed for EPRI doesn't provide all the details utilities need for planning purposes. But its concepts of dealing with multiple futures and sequential decision making can be adapted to the more complex planning models that utilities now use.

The Systems Program will develop its new approach by expanding the number of concepts the model can handle, using different utilities' data, accommodating broader demand uncertainty, and reviewing other decision variables.

A FRAMEWORK, NOT FINAL ANSWERS

Results of the California Energy Resources, Conservation, and Development Commission and EPRI studies highlight a crucial finding. Given all the uncertainties in utility capacity planning, it appears that attempts to reduce the costs of electric energy by controlling one or more of the uncertain factors will result in greater costs to consumers. Reduced planning reserve margin, for example, may lead to a power system so imbalanced that it is inefficient and expensive to operate. A better solution, EPRI suggests, would be to allow utilities some planned flexibility so they can react to the market forces of fuel supply and prices, demand for electricity, consumer expectations for reliable service, and so on.

"We're not claiming to have definitive, final answers or to tell utilities how to plan their systems," Karaganis emphasizes. "Our contribution is to offer this framework that allows everyone to pose questions and see which ones really turn out to be relevant. My personal feeling is that the more we can quantify relationships explicitly, the greater our chances are of finding solutions to our problems."

THE UTILITY INDUSTRY—VI

(By S. David Freeman)

The author of the next selection has had a profound and controversial influence on energy policy as head of the Ford Foundation's pioneering Energy Policy Project and as a member of the Carter Administration team that put together the National Energy Plan. Freeman's actions and opinions continue to be important and relevant to the topic of this reader, as chairman of the Tennessee Valley Authority.

Freeman's speech contains several points of interest, reflecting his new responsibilities. On the one hand, he reversed his former position on coal use, claiming "progress toward socially acceptable means of using" that fuel, and he skimmed over TVA's massive commitment to nuclear power with a pledge to demonstrate that radioactive waste "can be stored safely." On the other had, he cited TVA's program to make interest-free loans to residential customers for roof insulation, and a $7.7 million solar demonstration program, as evidence of the public utility's commitment to conservation and renewable energy sources.

[From Not Man Apart—Mid August/September 1978]

TVA's New Chief Plans To Stress Conservation[1]

(By S. David Freeman)

I'd like to thank President Alexander and the others who have put this conference together for inviting me here. I can't think of a better place to discuss future energy issues than a university campus and among the student population. The university always has been special in our society because it encourages the free exchange of ideas—even ideas that seem outrageous when first advanced.

The university is not only a place where people can speak their mind, but it is also the "factory" where new ideas are manufactured. There's hardly an instance where the breakthroughs in medicine, technology, social sciences, or agriculture haven't involved the hands and brains of the university researcher. And these accomplishments have been for the most part motivated by a social conscience—a desire to help the lot of the world, rather than striving for the almighty dollar.

ENVIRONMENTAL MOVEMENT

As we face the future we are going to need this same iconoclastic and adventurous spirit to help solve our energy problems. The issues before the public go far deeper than just demand and supply. They involve moral and ethical questions that will affect the way we live. And the jury is still out on which way we will turn.

It's my hope that this country will follow the lead of those who wish to build a durable society, one in which material goods are used without reckless abandon and with due regard to the needs of future generations. In order to accomplish this crucial objective, we need to start a grass roots movement to put the energy policies of this nation back in the hands of the people. This country can learn from the environmental movement which began right here in California as a grassroots effort about 10 years ago. There was a pitifully small but vocal group who began to shake the pillars of public opinion. They made it known that it was time to stop and take stock of the way the country was ravaging its air, land, and water.

They were joined by people in Appalachia who began to ask society if it wasn't wrong to strip the countryside for coal and leave the land scarred and torn. They also wanted to know why it was national policy to deep-mine coal for the betterment of the nation, without regard to the health damage to the miners themselves. And other concerned citizens questioned a policy that sanctioned pumping millions of tons of particulates and oxides into the air each day from the power plant smokestacks, damaging crops and lungs of people. They called for more attention to the problems of nuclear safety, and questioned a policy that took no action to provide a "trash can" for the deadly nuclear waste produced by nuclear weaponry and power plants.

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[1] Remarks before a conference on energy policy, Pomona Colleges, Claremont, California, April 20, 1978.

The resulting environmental laws saved our high energy civilization from a suicidal trend. The whistle blowers succeeded. The battle to save the planet will require eternal vigilance. But we now have a fair chance to succeed.

The energy crisis, of course is not really a crisis at all but something much worse. It is a test of our ability to innovate and change. It will require a rebirth of the traditional American spirit of innovation as the age of petroleum abundance comes to an end. The heart of the energy problem is indeed a shortage of domestic oil supplies today, and, in a very few years, a world shortage. The roots of the energy crisis go back to Henry Ford and the Wright Brothers, whose inventions resulted in rapidly increasing the use of petroleum. The country has since followed a policy of "drain America first," depleting most of our finite supply.

We now have developed an addiction for foreign oil that is a growing hemorrhage, costing our economy about $45 billion last year alone. As serious as it is, this dollar drain is still an abstraction with most people. In fact, with oil consumption down a little from last year, and with new supplies from Alaska, the impression is left that America is literally swimming in oil. But all this can change very suddenly if the nations in the Middle East decide to restrict production. Or the shortage can come on more gradually, much the same as air pollution has built up in our cities. In a sense, that could be more dangerous. In any event, if we drift along into the 1980s, the full reality of a dwindling petroleum resource will surely restrict the mobility and way of life of the average consumer. And there is a very real question whether a democratic form of government will be able to cope with the problem if we wait much longer in getting on with the urgent job of breaking the petroleum habit to which we are addicted.

ENERGY POLICY

To find our way out of the energy crisis will take a national energy plan of action. But we must remember that regardless of what plan emerges from the Congress, it's only a beginning. In essence what the President is trying to do is develop a national sense of purpose. How the plan will be carried out will be a local responsibility.

I'm not going to discuss the specifics of the current national energy debate. But we need to look at the underlying philosophies that have thus far caused a virtual stalemate.

A segment in this society still believes that we can produce our way out of disaster if only there is enough money put in the hands of big oil and other corporate giants to create an incentive to do it. This approach will require a relaxation of existing environmental laws because they are seen as "nonproductive" investments. Government would intervene to spur production but otherwise would "get off the backs" of industry and let the so-called free market allocate our resources. This means, of course, economic deregulation, allowing the price of oil to escalate to the world market price.

It is an appealing notion to oppose any government regulation and let the so-called free market balance our energy budget, but with a

50 percent shortage of domestic petroleum and the OPEC cartel fixing the world price, there is no competitive market. To turn the price of domestic oil and gas loose means monopoly-sized prices that would hurt or cripple many industries and impose gross inequities on families who couldn't afford to heat their homes or drive their cars. Thus, instead of increasing competition, the production-first approach is leading to the oil industry's control of coal and uranium production. The reason is obvious, they are the only ones that have the cash to do it. Decontrol would let the oil companies claim monopoly-sized profits and use the consumers' capital to buy up America's remaining fuel resources. Big Oil would own the lifeblood of a high-energy civilization. It is a recipe for corporate socialism and the end of small business and competition in the energy field.

I don't see our energy plan this way and neither does the President. The energy problems we face are so complex and urgent that federal intervention is essential to assure that energy inflation doesn't continue to plague our economy, to restrain energy waste, and to assure that the values and costs, external to market forces, such as environmental problems, human concerns and foreign policy are addressed by the proper levels of government.

In my view, we are in a new era in the relationship between energy and economic progress.

Historical patterns of energy production and use may very well work to reduce real growth. Pouring massive amounts of capital into fuel conversion plants that are energy inefficient will simply fan the flames of inflation and depress the economy. And it will mean an energy system run by large companies where the crucial decisions are beyond the control of local people.

Energy policy should match the best and most durable resources in each community with the real needs of local people. Efficiency, diversity, self-sufficiency, and environmental protection should be the watch-words of our energy future.

In the Tennessee Valley I believe we will be moving in just that direction. We are going to innovate and try to find some of the answers. And we propose to do it by using TVA as a national demonstration, just as it was intended when Franklin Roosevelt signed the TVA Act into law in 1933.

Congress in its wisdom clothed TVA with the power and flexibility of a private corporation to help the Tennessee Valley region's people, but it left no misunderstanding about TVA's greater role. On every TVA power plant are the words: "Built for the people of the United States of America." TVA began with seed money from the people of this country because it was a national experiment to find answers to pressing national problems.

TVA started life as an environmental protection agency, with its first task to plant a green cover over brown, eroded land. And with the help of the people, the Valley is largely rich and productive again. But TVA's job hasn't stopped there. The agency is responsible for stimulating regional development, which has meant improving the standard of living for a people whose per capita income once was less than half the national average, and who had to eke out a living from agriculture. Today most of the Valley's citizens have lifted themselves from the vise of poverty, and are enjoying decent work and a better life for their families. TVA has helped in a variety of ways and its success has rested with its closeness to the people.

TVA took on the challenge of getting the Tennessee Valley back in the mainstream of American life back in the 1930s, and today it is ready to help find the answers to the compelling energy problems that face this nation.

TVA can be a living laboratory for the nation. The area is blessed with a diversity of energy sources and it faces the same tough environmental problems that must be overcome in every part of this country.

COAL AND NUCLEAR

The region sits atop some of the richest coal reserves. Each year TVA steam plants use up to 40 million tons of coal. We are the nation's largest purchaser of coal. To find cleaner, more efficient uses of coal is an obvious must for TVA. It also is an obvious must for this nation. Today TVA is the number one air polluter in this country. We don't intend to remain in that embarassing position. I predict we will soon launch the nation's largest program to clean the air and preserve the land and set an example for other power systems across the land.

The TVA power system is of course well known for its large hydroelectric system, but TVA also has the largest nuclear power construction program in the nation. We serve more than 2.6 million electric consumers through locally controlled, consumer-owned distributors who can join in this experiment of finding the right combination of energy diversity.

I said a few years back that the only trouble with coal was "you couldn't mine it and you couldn't burn it." But, the world hasn't stood still. In many ways we are making progress toward socially acceptable means of using coal as a bridge toward a durable society based on natural energy.

On the consumption end, TVA already is using a wet-limestone scrubber, and is planning magnesium-oxide units to remove sulfur dioxide from stack gases and produce sulfuric acid as a usable byproduct. Recently TVA awarded a contract for the largest bag house installation in the country, which will remove tiny particulates from stack emissions—particulates which may be the most damaging to lungs.

And, we now have good laws on the books to control the evils of strip-mining and deep-mining coal. Effective enforcement of these laws must be demonstrated and TVA stands ready to play a constructive role toward that end.

TVA also has a compelling interest in resolving the problems of nuclear power. The disposition of nuclear waste presents a most disturbing problem. In my view, it's immoral for us to continue to generate electricity with nuclear plants without finding a "trash can" for the waste. Sure, the waste is in very small amounts, but it's also a deadly poison. For years the national government has studied this problem to death. At TVA we plan to demonstrate that the waste can be stored safely. If we cannot perfect retrievable storage for spent fuel in underground geologic formations, then we will build an aboveground facility that will store the waste safely for an indefinite period.

ENERGY CONSERVATION

The irony of the position of the production-first advocates is that they overlook our best bet. Energy conservation is the cheapest and quickest source of supply. The energy we save can fuel the growth in the economy as well as save consumers money.

Conservation must also be evaluated in terms of the problems of inflation and productivity. Energy is the most capital-intensive sector of our society, accounting for about 25 percent of total capital investments. It saves enormous amounts of capital required for more expensive generation. Considering the size of the energy sector, the American economy may be wasting as much as $100 billion over the next 15 years if we don't get serious about conservation programs. Conservation investments are the best way to fight energy inflation and keep our economy healthy.

We are proving that conservation really produces favorable results on the TVA power system. Currently TVA has underway a home attic insulation program that offers interest-free loans to consumers whose homes are heated or air-conditioned electrically. This means that more than one million homes are eligible for free energy surveys, and the cost of insulation can be paid back in the monthly electric bill. The lower energy costs pay for the insulation in about three years.

Thus, the insulation program alone will save an estimated billion kilowatt-hours per year and shave about 500,000 kilowatts from the peak demand of the system. This means that we save a $500 million investment. It's also obvious that inflation is boosting the cost of new generating units. So in a very real sense the production-first approach means higher electric rates for consumers while conservation investments will provide the same amount of power at a tiny fraction of the cost.

With a system as large as TVA's—about 28 million kilowatts in capacity and an economy growing 50 percent faster than the national average—conservation programs can pay incredible dividends.

Aside from the overall savings in long-range power system expenditures, there's a real human problem that conservation can help alleviate. All across this country electric rates have gone up. On the TVA power system, about one million homes use electric heating. For these consumers the average annual use can be more than 21,000 kilowatt-hours, about two and a half times the national average. Even though electric rates in the Valley region are about a penny per kilowatt-hour below the national average, and far below most parts of the nation, heavy use means large electric bills, especially in winter.

This puts a terrible burden on the low-income families who generally don't have well-insulated homes. The monthly electric bill in many instances rivals the mortgage payment. We in public power have a duty to help these people. We cannot ignore their plight. Conservation programs such as attic insulation can only be the beginning of a solution. We hope to set a standard for the nation.

SOLAR ENERGY

The logic of investing in conservation has equal application to solar energy and other renewable resources. At TVA, we have underway a $7.7 million solar demonstration program, to find out the best uses of the sun in the Tennessee Valley region. We will be considering a wide range of applications, including solar water heaters, solar heating for homes, and in the future, photovoltaic cells to turn sunshine into electricity. We also intend to use wood for heating—there are literally millions of kilowatts lying on the ground in our forests rotting away.

When it comes to solar, we repeatedly are told that this technology is not feasible and can't be counted on for any help with the energy problem in the near future. That's simply not true. TVA, in partnership with the people in the Valley, is going to demonstrate solar heating on an economical footing. We know a great deal about solar energy; all we need is to provide the consumer knowledge and front-end money to use it. We hope to help people plug into the sun and begin to unplug from the TVA power system.

I believe we can demonstrate that solar is a practical energy source, and it will certainly be an inflation fighter. The cost of the sun won't go up once the initial investment has been made. The savings will grow each year over the life of a home or building, which is 50 years or more, while the cost of other fuels keeps going up.

Solar power for homes and commercial buildings must be considered as a decentralized, locally controlled alternative to a remotely controlled, large power plant. For example, it takes about a $1 billion investment in a power plant to serve the needs of 100,000 electrically heated homes. I believe we ought to consider making that $1 billion investment in solar energy to achieve the same result. A new plant using coal or nuclear power started today will require fuel that will become more costly each year for three or four decades to come. Surely the solar equivalent looks more promising to the consumer. And TVA is duty-bound to allocate capital to the lowest-cost source for the consumer.

I don't know what eventually will happen, but we need to keep an open mind about our programs. The extensive use of renewable resources isn't a pipedream conjured up by utopians. It is here and now, and at TVA we intend to demonstrate for the country that it can be done.

TVA's strength in the past stemmed from the fact that it is a decentralized, grass-roots agency that stressed local, individual participation in the TVA program. As David Lilienthal so well stated in *TVA: Democracy on the March:* "The physical job is going to be done; of that I think we can be sure. But . . . if the people are denied an active part in this great task, then they may be poor or they may be prosperous, but they will not be free."

TVA practiced participatory democracy long before that phrase became part of today's lexicon. The support, understanding, and involvement of people is the key to TVA's future success. I would hope that TVA can be a source of pride and an example of accomplishment as America makes the transition from the era of lavish use of finite resources to a durable society.

SOLAR ENERGY—I

(By Joseph G. Asbury and Ronald O. Mueller)

Solar energy is the major alternative being considered as a substitute for central electric power. Ideally, decentralized solar installations could either substitute completely for electricity used for heating, or could be merged into a joint system with electricity used for back-up as necessary.

As the next selection indicates, use of electricity as a back-up for solar heating systems does not make for a very good technological match, basically because both systems are very capital intensive. The problem of spreading the cost of substituting solar power equitably among all the utility's customers without discouraging commercialization of solar systems is a thorny one. One alternative is put forward in the selection following this one.

[From Science—Feb. 4, 1977]

SOLAR ENERGY AND ELECTRIC UTILITIES: SHOULD THEY BE INTERFACED?

(By Joseph G. Asbury and Ronald O. Mueller)

Solar energy technologies and their applications constitute a broad and diverse array of energy supply options. Solar systems are currently under development for applications in the generation of electric energy, production of industrial process heat, and heating and cooling of buildings. The identification of promising solar applications and the elimination of unpromising ones are necessary for the efficient development and use of the solar resource. In applications where solar systems are interfaced with conventional supply systems, it is important that the solar systems be evaluated in context with the cost and performance characteristics of the conventional systems that they are designed to supplement or replace.

A number of investigators have proposed solar energy systems that interface with conventional electric utility supply systems. Whether considering solar thermal conversion systems to produce electric utility power or solar systems for thermal applications in buildings, the systems' designers have generally concluded that solar energy can reduce electric utility fuel and capital requirements. In both utility power system and utility customer end-use applications, solar energy saves fuel directly by substituting for utility fossil and nuclear fuels. Utility capital and indirect fuel savings occur as a result of the ability of the storage system, always included in the solar system design, to displace the solar system's auxiliary energy requirements to off-peak hours. The effect is to reduce the utility's peak-period loads from those which would otherwise occur, thereby allowing the substitution of base-load plant and fuels for peak- and intermediate-load plant and fuels.

Recent investigations of certain solar heating and cooling systems have emphasized that solar insolation outage can be covered entirely with inexpensive off-peak electric power [1]. All that is required is the incorporation of a thermal storage system with capacity adequate to meet the design-day building load. What these studies have failed to point out is that the inclusion of thermal storage effectively reduces the function of the solar collector component of the solar energy system to the displacement of off-peak electric energy. This fact greatly diminishes the economic benefits that can be attributed to solar energy systems.

It is the purpose of this article to reevaluate the economics of solar energy systems that interface with conventional electric utility supply networks. The reevaluation proceeds along two paths. First, adopting the implicit assumption of many solar system designers that there are abundant supplies of low-cost off-peak electricity, we undertake systems studies of several of the more important solar energy applications.

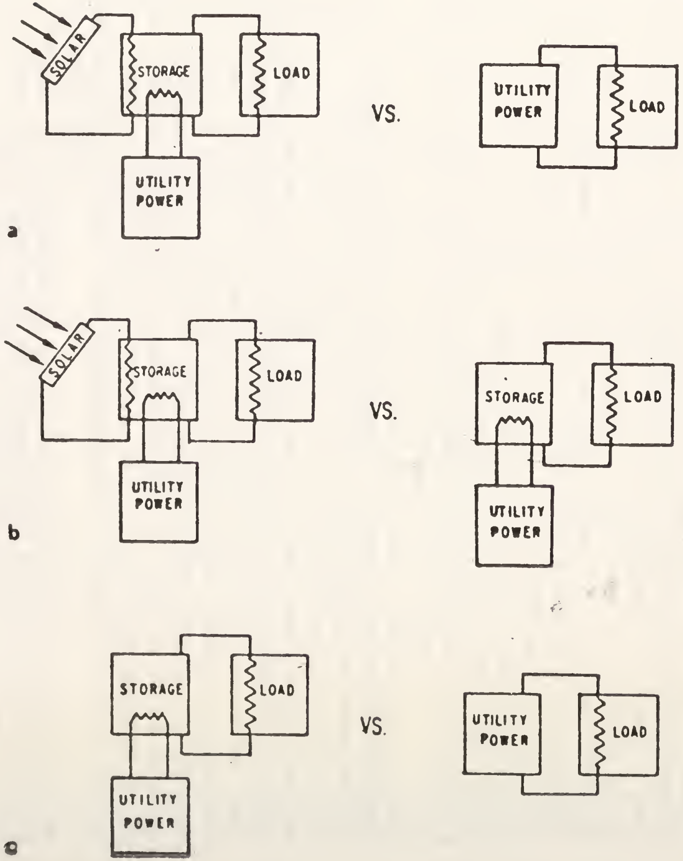
Second, adopting a standard economic approach to the periodic load problem, we examine the general problem of interfacing solar energy and electric utility supply systems.

A central theme of the systems studies is that solar energy systems are most logically compared with the storage-augmented versions of the conventional systems that they are designed to supplement or replace. Adopting this approach, we estimate solar collector break-even costs for solar/electric-resistance and solar/heat pump systems for space heating and solar thermal conversion systems for electric power generation. For solar/electric-resistance heating, the upper bound on solar collector break-even costs is found to be approximately $30 per square meter (≈$3 per square foot) if auxiliary energy is from coal-fired utility generating plants and $75 per square meter if auxiliary energy is from oil-fired utility plants. For all the solar/heat pump configurations examined, the collector break-even costs are found to be substantially lower than for the comparable solar/electric-resistance heating systems.

The general problem of interfacing solar energy and electric utilities is treated by analyzing the economics of solar collection in terms of two alternative scenarios. In the first scenario, off-peak electricity, even if priced at variable cost (utility fuel cost), remains available for the indefinite future. (This corresponds to the economists' firm-peak case.) In the second scenario, through the introduction of either simple off-peak price discounts or time-of-use pricing, the utility's load curve becomes flat (shifting-peak case). For the first scenario, it is shown that solar collection systems generally will be economical only if they can deliver solar energy at a cost lower than the variable (fuel) cost component of off-peak electricity. In regions of the country where the utility off-peak fuel is coal or nuclear fuel, this implies very low solar collector break-even costs. In regions of the country where the cost of off-peak electricity is higher than that of other auxiliary energy forms—the utility fuel is oil—the most economical and energy-conserving solar systems will not interface with the electric utility. For the second scenario, the economic benefits of solar collection in most applications are found to be approximately equal to the value of the displaced utility fuel, indicating break-even points for solar collectors that are roughly equal to those under the first scenario.

The general conclusion of this article is that solar energy systems and conventional electric utility systems represent a poor technological match. The basic problem is that both technologies are very capital intensive. The electric utility, because of the high fixed costs of generation, transmission, and distribution capacity, represents a poor backup for solar energy systems. On the other hand, the solar collection system, because it represents pure, high-cost capital and because of the periodic nature of its output, should not be considered as a part-load source of auxiliary energy for the electric utility. Viewed in this context, the low break-even costs established for solar collector systems that interface with electric utilities are merely symptomatic of the problem of matching two technologies that in important respects may be incompatible.

Because of our extensive use in this article of the concept of solar collection break-even cost, it is important from the beginning to point out that (i) these costs are always calculated by directly comparing the capital and fuel requirements of conventional systems with those of solar systems providing services of comparable quality, and therefore (ii) break-even cost values, where presented here, are dependent on the costs assumed for the conventional technologies, but (iii) the qualitative conclusions reached are essentially independent of the exact break-even cost values. We do not explicitly examine passive solar building concepts that modify and reduce normal thermal load requirements, nor do we analyze intermittent solar concepts (for example, air-conditioning systems without adequate backup to cover solar outages) for which there are no conventional counterparts. As shown below, the upper-bound break-even costs of solar collection are effectively "pinned" to the value of off-peak utility fuel. By stating break-even costs in terms of current prices of off-peak utility fuel, we effectively neglect: any price-distorting effects of government development of subsidy program, the many environmental spillover benefits that are commonly associated with solar energy, fuel conservation benefits beyond those reflected in current prices of utility fuel, and the possibilty of fuel price escalation beyond the general inflation rate over the lifetime of the solar system [2]. However, none of these factors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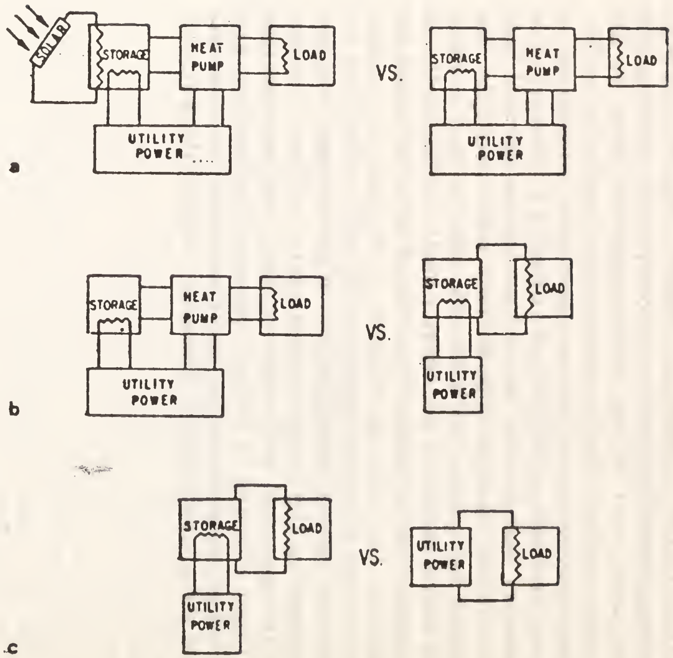
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Fig. 1 (left). Comparisons among solar, storage, and conventional space heating systems. Fig. 2 (right). Comparisons among solar-assisted heat pump, storage, and conventional space heating systems.

are likely to significantly affect the economics of solar systems that interface with electric utilities relative to the economics of solar systems that do not.

SOLAR/ELECTRIC-RESISTANCE HEATING

The reconceptualization necessary to properly assess solar heating systems that interface with conventional electric supply systems is shown in Fig. 1. Instead of comparing the cost of the solar heating system including storage with the cost of the conventional heating system (as in Fig. 1a), the solar system designer should compare the cost of the solar-supplemented storage heating system against the cost of the simple storage heating system (Fig. 1b). In practice, the latter comparison will proceed only after the benefits of storage heating relative to direct heating have been determined (Fig. 1c). It is our contention that most of the electricity supply savings claimed for solar energy systems stem from the storage, rather than the solar, component of the systems.

That storage heating systems are cost-effective in service areas supplied by winter-peaking utilities is well established [3]. A recent study indicates that the utility savings, mostly capital savings, exceed the thermal energy storage costs by a factor ranging from 2 to 4 [4]. The important consideration for the design of solar systems is that, given a storage capacity adequate to meet the design-day heating load, it makes economic sense to add a solar collector system only to the extent that it is cost-effective to substitute solar energy for off-peak electric energy. This consideration establishes an upper bound on acceptable solar collection costs:

$$C < S \cdot E$$

Here C is the annualized cost (dollars per square meter per year) of the installed collector system (including the costs of piping, pumps, controls, heat exchanger, and the collector itself), S is an upper limit on the amount of solar energy collected (kilowatt-hours thermal per square meter per year), and E is the cost of supplying off-peak electricity (dollars per kilowatt-hour electric). For many regions of the country, a representative value for the cost of supplying off-peak energy is 10 mills per kilowatt-hour (=\$0.01/kwh), which covers base-load fuel costs (≈\$1 per 10^6 Btu) and base-load operating and maintenance costs. Under efficient cost allocation rules, all utility capital expansion costs should be charged against energy use during other time periods [5]. An optimistic level of solar collection over the space heating season is 300 kwh m^{-2} $year^{-1}$ (=100,000 Btu per square foot per year). Because, for a fixed storage capacity, annual collection efficiency decreases with collector area, this figure represents an upper limit on solar collection. Inserting these values for electricity cost and solar energy collection into the relation above, we obtain an upper bound on the break-even cost of the solar collection system of \$3 m^{-2} $year^{-1}$. If the real capital recovery rate is 10 percent per year, this corresponds to an upper bound on collector system costs of \$30/m^2 (≈\$3 per square foot). This is a very low break-even value compared with estimates based on either the average or the peak-period cost of electricity supply. The upper bound on the break-even cost is \$75/m^2 if the auxiliary energy cost is 25 mills/kwh.

In service areas supplied by summer peaking utilities, storage space heating generally is not cost-effective. In such service areas, the displacement of daily winter peak loads into nighttime valleys does not reduce the utility's annual peak capacity requirements. That the addition of a solar collector system could be cost-effective in this situation appears highly improbable. Having to support a sizable portion of the investment in the storage system, the return on the investment in the collector system will have to be higher than for the winter-peaking service area. The break-even cost of the solar collector will be correspondingly lower and may even be negative.

Solar-assisted electric hot water heating may justify a higher collector cost than solar space heating. Solar hot water systems enjoy a better duty cycle, displacing off-peak electricity on a year-round basis. On the other hand, solar hot water systems suffer a disadvantage relative to simple storage systems. This stems from the small additional cost of storage hot water heaters over conventional systems. Usually all that is required is a somewhat larger tank with improved insulation. The addition of a solar collection system, however, usually involves the addition of a separate preheat storage tank. A similar cost burden occurs in solar space heating applications when, in order to improve solar collection efficiency, separate storage systems are incorporated in both the solar supply loop and the backup electric supply system.

SOLAR ENERGY/HEAT PUMP SYSTEMS

Solar heating systems more complex than the ones described above have been proposed. In particular, the solar-assisted heat pump has received considerable attention [6]. In one version of this system, the output of the solar collector is first input to a storage reservoir on the cold side of the heat pump [7]. The solar energy is removed from the reservoir by the compressor action of the heat pump and is delivered to the building load.

The principal advantages of the solar-assisted heat pump are the lower temperature required for the output of the solar collector and the improved heat pump performance because of the solar warming of the input reservoir. According to the system's advocates, this allows the use of a much lower cost solar collector, thus improving the break-even economics of solar heating. However, as shown below, another effect of incorporating a heat pump in the solar system design is to drive down the break-even cost for the solar collection sytsem.

The same techniques used in evaluating solar systems that interface with resistance heating can be used to analyze the solar-assisted heat pump design. Figure 2 presents a set of system comparisons building from direct resistance heating to the solar-assisted heat pump system. One of the steps in the system evolution in Fig. 2 represents an inferior progression and has been included only to facilitate the analysis. The system incorporating a heat pump in Fig. 2b is inferior to the system without a heat pump.

The heat pump operating solely off the electrically augmented storage on the input side is deficient on a number of counts. Because the heat pump can extract no more energy from the storage than is input, supplemental off-peak electricity is more efficiently stored and recovered in the system on the right side of Fig. 2b, where no work of compression is involved. The heat pump system is also more capital intensive, requiring a higher initial customer investment and greater utility capacity to meet the heat pump's contribution to the utility's daily peak load. As will become clear below, the inclusion of the heat pump with an electrically augmened input reservoir in Fig. 2 is simply part of a gedanken experiment to determine the overall cost-effectiveness of the solar-assisted heat pump system.

The system comparison in Fig. 2a lends itself to a particularly simple interpretation of the role of the solar collector subsystem. The system on the right side can be conceived as operating in almost the same way as its solar counterpart, the only difference being that the electrical energy is input to the right-hand storage reservoir during off-peak nighttime hours, while the solar energy is input to the left-hand reservoir during daytime hours. Although, as described above, this use of electricity is extremely inefficient, it amounts to no more than a simulation of the use of the solar energy that is input to the solar system.

Viewed in this context, the gross benefit from the addition of the solar collector to the heat pump system is no greater than the benefit realized when a solar collector is added to a solar-resistance heating system, namely the displacement of off-peak electric energy. However, now the gross benefit must also cover (relative to the solar-resistance system): the added capital cost of the heat pump over the resistence system, the utility capital costs associated with the supply of electricity to the heat pump during on-peak hours, and the cost of utility energy to run the heat pump. For the fraction of time when solar energy is not available, the heat pump can run off ambient air. This does not alter the relative economics of the solar-assisted heat pump and the storage heat pump in the comparison in Fig. 2a, because both systems would benefit equally from this option. However, it would reduce the heat pump cost burden slightly by the amount of the additional off-peak electricity displacement credit.

The additional capital cost of the heat pump system relative to the resistance system, after an air conditioner capital cost credit, is approximately \$1000 [8, 9]. For a nominal collector area of 50 m^2, this corresponds to a reduction relative to the break-even point for the collector subsystem in the solar-resistance system of \$20/m^2. In service areas supplied by winter-peaking utilities, a more significant cost penalty is the utility capital cost of meeting the design-day compressor load [10]. This cost, covering utility demand-related capital expansion costs at the generation, transmission, and distribution levels, amounts to approximately \$500 per peak kilowatt, corresponding to \$2000 for the heat pump and \$40/m^2 for the 50-m^2 collector. The break-even point is then −\$30/m^2 if auxiliary energy costs are 10 mills/kwh and \$15/m^2 if auxiliary energy costs are 25 mills/kwh.

In a service area supplied by a summer-peaking utility, utility winter peak-day capacity costs are considerably lower, depending on such considerations as reserve margin under scheduled maintenance outage. However, even if utility power costs are assumed to be negligible, the break-even point for the solar collector component of the solar-assisted heat pump system will be lower than that of the solar/electric-resistance heating system by the amount of the added capital cost of the heat pump.

Another solar energy/heat pump design concept is illustrated in Fig. 3. Here, the storage reservoir is on the "hot" side of the heat pump and both the solar collector and the heat pump deliver energy directly to the reservoir. We shall not analyze this system in any detail here [11]; however, it can readily be shown that this system is always inferior to the solar-assisted heat pump analyzed above. The basic problem with the system design in Fig. 3 is that it quite literally forces two capital-intensive subsystems, the solar collector and the heat pump, to compete rather than supplement one another in supplying the heating load.

The conclusions reached regarding these two generic types of solar energy/heat pump systems appear to be applicable to all solar/heat pump configurations. Our analyses of other heat pump concepts indicate that they can always be evaluated by decomposition into some combination of the solar/resistance-heating and the two solar/heat pump concepts described above. All the solar/heat pump concepts that we have identified have break-even solar collection costs considerably lower than the break-even solar collection costs of the solar/resistance-heating system in Fig. 1.

SOLAR ELECTRIC POWER GENERATION

Many of the same kinds of trade-offs affecting the economics of solar energy applications in buildings affect the economics of solar electric power generation. Figure 4 presents the solar electric analogs of the heating system comparisons presented in Fig. 1.

The usual procedure for determining the cost-effectiveness of a solar electric generating system is the comparison indicated in Fig. 4a. The cost of the solar electric system, including any necessary backup to cover solar outage, is compared with the cost of the conventional generating system. In Fig. 4a the comparison is presumed to be between the solar system including its backup boiler and a conventional intermediate generating plant. (To facilitate later analysis, a base-load generating plant has been included on both sides of Fig. 4a. This facility cancels out in the comparison.) Although the comparison in Fig. 4a is the standard method of evaluating solar electric systems, a more meaningful comparison is that shown in Fig. 4b.

That a solar electric system can survive comparison with a storage-augmented base-load generating plant is very doubtful. Given low-cost storage, a storage-augmented base-load plant can replace a combination of base and intermediate (or peaking) plants (see Fig. 4c). In a recent study, the Public Service Electric and Gas Company [12] calculated break-even costs for thermal storage in this application at $570/kw (10-hour storage device) and $320/kw (5-hour storage device) [13]. On the other hand, in a Fig. 4a-type evaluation of the economics of solar electric power systems, the Aerospace Corporation [14] assumed solar storage device costs several times lower than the PSE&G storage break-even costs. For the most attractive solar electric application examined in the Aerospace study (a central station receiver plus 6-hour storage compared to an intermediate generating plant), the heliostat effective break-even cost was about $30/m^2. Already a difficult cost objective to achieve, the break-even cost would have been considerably lower if the solar electric system had been compared against a storage-augmented base-load generating plant.

GENERALIZATION

The preceding analysis was limited to the types of solar systems that interface with electricity supply systems. In considering such systems, we stressed the low break-even costs of solar collection systems whose only effect is to substitute solar energy for low-cost off-peak electricity. The question naturally arises as to how the break-even economics would be affected by the absence of low-cost off-peak electricity.

In an important sense, off-peak electric power is merely a by-product of on-peak electricity. However, its future availability might very well diminish as utilities and regulators begin to price it at cost and customers respond by purchasing it in increasing quantity. The European experience indicates that, given adequate customer price incentives, the time required for complete "valley filling" for a winter-peaking utility system can be as short as 10 to 15 years [2]. Therefore, to complete our analysis of solar energy systems that interface with electric utility systems, we will generalize our results by considering two alternative scenarios. In the first scenario, off-peak electricity, even if priced at variable cost (utility fuel cost), remains available for the indefinite future; in the second scenario, as a result of the introduction of a new technology or the implementation of some form of peak-load pricing, the utility's load curve becomes flat. The first scenario corresponds to the economists' firm-peak case; the second scenario to the shifting-peak case.

In the first scenario, in most parts of the country off-peak electricity will remain the lowest-cost auxiliary energy available for solar energy systems. Systems that use this form of auxiliary energy will represent the economically (and socially) most efficient solar energy systems. Thus, to be economical, solar collection systems will have to be low enough in cost to supply solar energy that is cost-competitive with off-peak electricity.

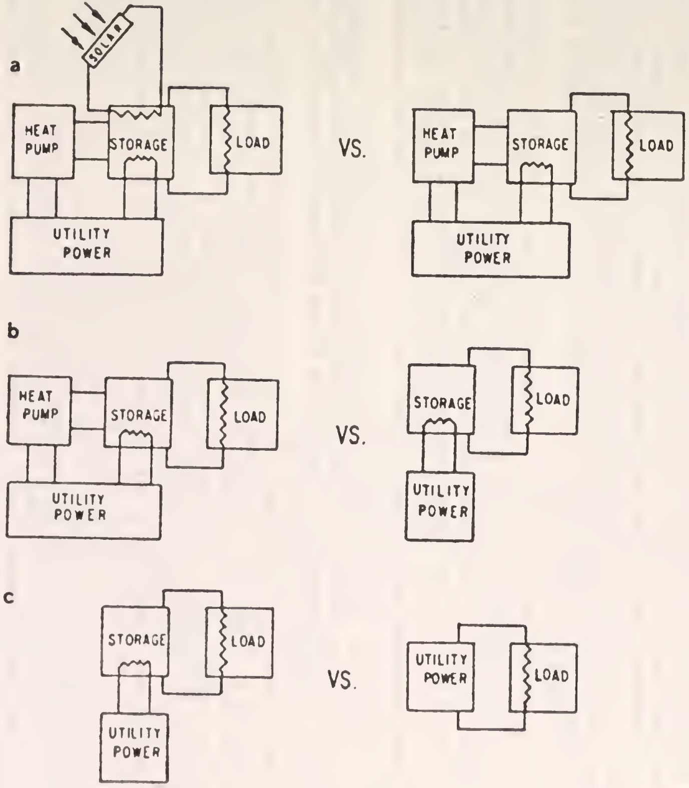
Even in the first scenario, there may remain many utility service areas where off-peak electricity is not the lowest-cost source of auxiliary energy. Today, many utilities use oil in base-load generating plants, with the cost of the oil approximately $87 per metric ton ($13 a barrel). After correction for transmission and distribution losses, this gives a cost of approximately 25 mills/kwh ($8.40 per 10^6 Btu). On the other hand, the price of home heating oil is currently about 11 cents per liter (42 cents per gallon), which after correction for furnace conversion efficiency is equivalent to approximately 15 mills/kwh ($5 per 10^6 Btu). Thus, in service areas supplied by utilities using oil-fired base-load plants, home heating oil represents a lower-cost auxiliary energy form. Although natural gas may also be used to supplement solar systems, its price (marginal cost) under national deregulation is likely to be somewhat higher than the price of oil.

To summarize, the findings for the scenario involving indefinitely available low-cost off-peak electricity are as follows. In service areas supplied with electricity from coal or nuclear generating plants, the most economical solar energy systems will be those that use off-peak electricity as the auxiliary energy source. Accordingly, solar collection systems generally will be economical only if they can deliver solar energy at a cost lower than the cost of off-peak electricity. As we have already seen, the upper limit on break-even costs is about $30 per square meter of collector area. In service areas supplied with off-peak electricity produced from expensive fuels, such as oil or natural gas, the most economical solar energy systems will be those that utilize auxiliary fuels other than off-peak electricity. In these service areas the most economical solar systems will not interface with the utility supply system.

Probably a more meaningful test of the interfacing of solar systems and electric utility systems occurs in the second scenario, when the utility load curve is flat. This can occur if the utility, through the application of a judicious pricing strategy (higher prices during high-demand hours than during low-demand hours), manages to equalize the rates of consumption during all the subperiods of its demand cycle. In this case, the demanders during each subperiod press against the utility's capacity and are responsible, in varying measure, for the utility's long-run expenditures for capacity expansion [15].

In this situation, the effect of a solar heating system on the utility's load curve and on its unit cost of supply can be conceived as occurring in the following way. Let us assume that the utility takes into account the effect of solar outages by setting its high-demand and low-demand subperiod prices such that consumption during the low-demand period, including consumption required to cover worst-case solar outage, is equal to consumption during the high-demand period. It follows, in this case, that utility capacity is underutilized during the demand cycles when solar insolation is available for home heating. Solar energy still serves to displace utility fuel; however, the underutilization of utility capital relative to its rate of utilization in supplying a simple electric storage heating system raises the unit cost of electricity supply. This added cost, which represents a real increase in the capital component of electricity cost, must be incorporated, ex ante, into the higher unit price charged solar heating customers than charged storage heating customers. From the solar heating customer's perspective, the increase in unit price is exactly offset by the zero variable-cost component of energy from the customer's solar collection system. (The utility's capital investment and the total energy consumed by the customer are unchanged.) Thus, just as for the firm-peak case, the net benefit of solar collection for the customer, and for society as a whole, is equal to the value of the displaced electric utility fuel. [This result can be shown to follow from a general analysis of the periodic load problem [11].]

Although in the preceding discussion of the shifting-peak case we have implicitly assumed the existence of only one type of utility plant, this is not a serious limitation for most solar applications. In home heating applications, for example, the fraction of the load for which solar substitutes for electric supply will not be sufficient, of itself, to allow the utility to substitute intermediate-load for base-load plants. In central station electric power applications, solar must compete directly against base-load plants, the only plant type in use under the uniform load, shifting-peak case.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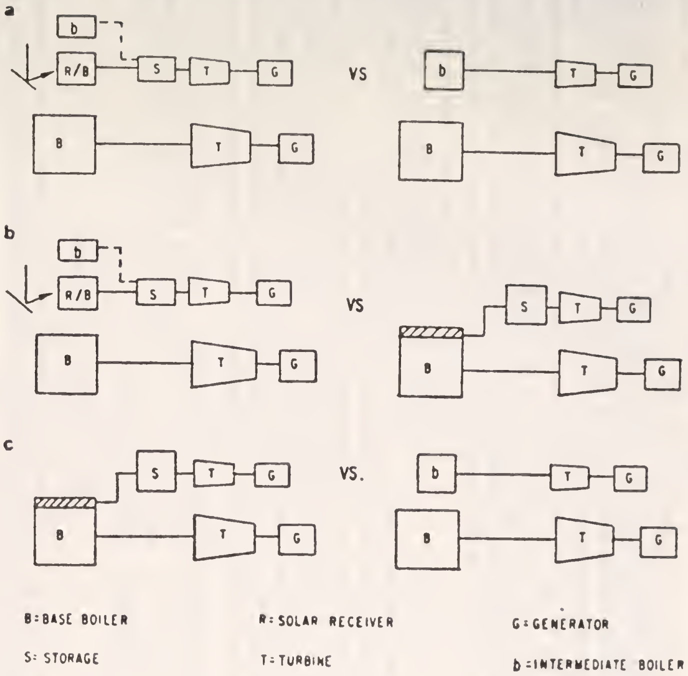
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B: BASE BOILER
R: SOLAR RECEIVER
G: GENERATOR
S: STORAGE
T: TURBINE
b: INTERMEDIATE BOILER

Fig. 3 (left). Comparisons among solar/heat pump, storage, and conventional space heating systems. Fig. 4 (right). Comparisons among utility solar thermal conversion, thermal storage, and conventional power generation.

SUMMARY

Analyses of the economics of solar collection in the firm- and shifting-peak cases (that is, with off-peak electricity indefinitely available or with a flat load curve) indicate that, for many important applications, solar energy systems that interface with electric utiliies can be justified only in terms of the value of the off-peak utility fuels that they displace. In regions where off-peak electricity costs are low, the most economically efficient solar energy systems, will be those that use electricity as the auxiliary energy source. This implies extremely low break-even costs for a number of important solar energy applications. In regions where the cost of off-peak electricity is higher than that of competing energy forms, the most economical solar energy systems will utilize auxiliary fuels other than electricity.

The general conclusion is that conventional electric utility systems and most solar energy systems represent a poor technological match. The basic problem is that both technologies are very capital intensive. The electric utility, because of the high fixed costs of generation, transmission, and distribution capacity, represents a poor backup for solar energy systems. On the other hand, the solar collection system, because it represents pure, high-cost capital and because of its outage problems, cannot be considered as a part-load source of auxiliary energy for the electric utility system.

REFERENCES AND NOTES

1. See, for example, P. J. Hughes, W. A. Beckman, J. A. Duffie, paper presented at the Sharing the Sun Conference, Winnipeg, Canada, August 1976. See also *Solar Engineering Magazine* (August 1976), p. 24.

2. Basing the break-even cost for the solar collection system on the current price of base-load fuel is equivalent to assuming that the real rate of increase of the price of base-load fuel less the real time rate of discount of money is zero. This appears to be a reasonable assumption. See, for example; Staff Report, Executive Office of the President, Council on Wage and Price Stability, *A Study of Coal Prices* (Washington, D.C., March 1976); J. G. Asbury and K. Costello, *ASME Publ. No. 76-IPC-PWR-7* (May 1976).

3. J. G. Asbury and A. Kouvalis, *Argonne Natl. Lab. Publ. No. ANL/ES-50* (April 1976). Although the storage components on either side in Fig. 1b are drawn the same, the storage devices used in electric storage heating systems are generally of higher quality or lower cost than the storage devices used in solar systems. Under worst practice, the same storage device used in the solar system can be incorporated in the storage heating system. The principal advantage of storage in electric storage heating is the high temperature, up to 1200°F, that can be achieved in magnesite bricks or other materials.

4. J. Asbury, R. Giese, S. Nelson, L. Akridge, P. Graf, K. Heitner, "Assessment of Energy Storage Technologies and Systems (Phase 1): Electric Storage Heating, Storage Air Conditioning and Storage Hot Water Heaters," *Argonne Natl. Lab. Publ. No. ANL/ES-54* (October 1976).

5. See, for example, C. Cicchetti, W. Gillen, P. Smolensky, "The Marginal Cost and Pricing of Electricity: An Applied Approach," *Natl. Sci. Found. Rep. STA 74-24370* (June 1976); L. T. Mahoney, Jr., National Economic Research Associates, Inc., testimony at a hearing before the Public Service Commission of New York, Case No. 26806, January 1976; testimony at a hearing before Public Service Commission of Wisconsin, Docket No. 6630-ER-2, December 1975; J. G. Miller, Wisconsin Power and Light Company, testimony and exhibits at a hearing before the Public Service Commission of Wisconsin, Docket No. 2-U-8085, April 1976.

6. S. F. Gilman, Ed., *Solar Energy Heat Pump Systems for Heating and Cooling Buildings—Workshop Proceedings* (Pennsylvania State Univ. Press, University Park, and ERDA Technical Information Center, Oak Ridge, Tenn., 1975).

7. See, for example, V. D. Karman, T. L. Freeman, J. W. Mitchell, "Simulation study of solar heat systems," paper presented at the Sharing the Sun Conference, Winnipeg, Canada, August 1976.

8. Gordian Associates Incorporated, "Evaluation of the air-to-air heat pump for residential space conditioning," report prepared for the Federal Energy Agency under contract FEA-CO 04-50171-00, April 1976.

9. As shown in (8), the cost of a heat pump sized to meet the cooling load is approximately $1000 greater than the cost of an air conditioner. This cost difference holds approximately for most regions of the country. Although the heat pump is less efficient in the air-conditioning mode than the standard air conditioner, this charge against the heat pump is ignored here. None of the solar-assisted heat pump concepts considered here use solar energy when the heat pump is operating as an air conditioner.

10. We ignore the resistance component of the heat pump's design-day power demand. For the system design concept examined here, energy can in principle be input to the storage reservoirs during nighttime hours to eliminate the following day's on-peak resistance power requirement.

11. For a detailed analysis see J. G. Asbury and R. O. Mueller, *Argonne Natl. Lab. Publ. No. ANL/ES-52* (August 1976).

12. Public Service Electric & Gas Co., "An assessment of energy storage systems suitable for use by electric utilities," report prepared for the Energy Research and Development Administration under contract E(11–1)–2501 and the Electric Power Research Institute under research project 225, July 1976.

13. These break-even storage costs correspond to PSE&G's "typical values" for generating plant capital and fuel costs. The PSE&G also calculated break-even cost ranges corresponding to variations in input costs. The PSE&G typical value conventional-plant generating cost are similar to those used in the Aerospace study cited below.

14. Aerospace Corp., "Solar thermal conversion mission analysis—Southwestern United States." report prepared for the National Science Foundation under contract NSF–C797, January 1975.

15. For the efficient-price solution, see O. Williamson, *Am. Econ. Rev.* 56, 810 (1966); M. Crew and P. Kleindorfer, *J. Polit. Econ.* 79, 1369 (1971).

16. We thank E. Croke for a very helpful suggestion and R. Giese, S. Nelson, and V. Rabl for a number of useful comments. Supported by the Chemical and Thermal Energy Storage Branch. Division of Energy Storage Systems, Office of the Assistant Administrator for Conservation, Energy Research and Development Administration.

SOLAR ENERGY—II

(By John K. Freeman)

In this article, the various possible approaches toward solar power by a utility are discussed. These include a hands-off approach; preferential rates for utility-approved solar uses; active utility participation in the sale, installation and financing of solar systems, and the most active approach in which the utility would "treat the dispersed solar system installed in the customer's residence as utility property for rate-making purposes." The major portion of the article is devoted to a discussion of this fourth option.

Utility ownership of dispersed solar equipment would, of course, bring the solar option to some degree into the centralized power generation system, thus eliminating one philosophical advantage to the decentralized technology. The author discusses it because he suspects that "the extent of market penetration and consumer satisfaction resulting from a tax credit program may turn out to be disappointing." If, he says, "the need for a massive and rapid solar effort becomes critical, a utility rate base approach may turn out to be the most equitable and effective method."

[From Public Utilities Fortnightly—Jan. 5, 1978]

UTILITY ALTERNATIVES FOR SOLAR ENERGY

(By John K. Freeman) [1]

Solar energy has been utilized in a limited fashion for thousands of years in areas where climatic conditions, economics, and human ingenuity have been supportive.

Today, no other source of energy has captured the public's imagination as effectively as turning sunlight into usable energy. Media reporting has spotlighted such individual efforts as a New York city cooperative which generates electricity with a rooftop windmill, a Colorado architect who heats his home with active and passive solar devices, and so on. Attention is focused on energy savings with little analysis of the material costs or man-hours needed to construct those installations.

To some environmentalists, solar energy is an inexhaustible and limitless form of energy which appears to be significantly less disruptive to our physical environment than the traditional fossil fuels and nuclear power. To some consumer advocates, the sun represents a potentially "free" source of energy which can be directly captured by the individual user. To some scientists and engineers, solar energy represents technology's response to the energy crisis. To most utility executives and the regulatory officials, solar energy is a question mark. How can a utility company demonstrate its support for solar energy but not be accused of preempting or monopolizing solar energy?

Presently the American public and many government officials have a love-hate attitude toward the utility industry. Rising utility rates, the East coast blackouts, and last winter's natural gas shortage have all combined to create public skepticism about the ability and proper role of the utility industry in solving the energy crisis. On the other hand, the utility industry has the technical capability, personnel, and capital which have resulted from decades of growth and service to a vast industrialized society. Certainly, these human and financial resources represent one of our greatest national assets.

The utility industry has a role and responsibility in the successful introduction of solar energy into our nation's energy inventory. There are several possible strategies which can be adopted by a utility. I would like to identify and briefly analyze some of the issues associated with these alternative strategies.

First, one must differentiate between centralized solar generation of electricity and dispersed solar systems which utilize electricity, natural gas, or fuel oil as a supplement or complement to the solar system.

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In the case of centralized power generation, a number of promising technologies are being pursued by public and private research efforts. Photovoltaics, wind energy, solar thermal, ocean thermal, and, perhaps, other even more exotic technologies may ultimately provide significant sources of energy to the utility system. These solar generating sources will need to compete economically and technically with traditional sources. These applications for solar energy will also need to be evaluated with respect to demand characteristics on the system, storage requirements, and regulatory policies regarding treatment of capital costs versus operating expenses. While the central solar generation facility will present some unique problems to the utility manager and the utility regulator, these problems will not be fundamentally different from those issues being confronted now with respect to alternative types of generating capacity.

Therefore, in each utility service area the climatic factors such as solar insolation, wind characteristics, and others, and the cost competitiveness of the solar electric generation technologies should be the determining factors in how aggressively a utility would pursue a solar strategy. This particular solar option for central generation is, of course, limited to electric utilities.

In the case of decentralized or dispersed solar energy systems the choice of utility strategies becomes much more complex. Traditional rate-setting procedures, especially the declining block rate structure, have come under heavy criticism. "Cost tracking" in rate structure has become the fashionable objective. Utility rate reform is now one of the central issues being debated as part of a national energy policy. Time-of-use pricing, load management, and related techniques are being widely discussed as measures for achieving equitable distribution of true energy costs among various types of consumers and for providing the maximum incentive for the efficient use of energy. As we attempt to apply these new rate concepts to existing utility activities, several factors emerge:

(1) Putting the theory into practice is hard.

(2) Each utility system is unique—demand characteristics including seasonal and daily peak loads and supply configuration including cost and type of generating capacity will vary considerably between regions and even within a state or region.

(3) Administrative complexity and consumer understanding of rate structure must not be ignored in the search for an economically pure set of rate policies.

(4) Conflicting objectives will not be totally resolvable and therefore some compromises must be struck if a better rate structure is to be adopted promptly.

(5) And, finally, there is no right answer. At best, current revisions will serve temporarily while better data are being gathered concerning demand projections and supply costs. The revised rate structure will in fact itself trigger a response in the overall system's behavior which will provide feedback in the form of a new supply and demand relationship.

Understanding all of these factors becomes even more elusive when dispersed solar energy is introduced into a utility system. First of all, there is no such thing as a standard solar system. A typical solar system:

May include water heating, space heating, or air conditioning, *May* be sized to supply from 30 per cent to 80 per cent of the household's energy consumption.

May have one to three days of storage,

May utilize a heat pump, electric resistance, gas, or fuel oil as a backup energy source, and

May be designed to utilize off peak charging of thermal storage.

For a rate structure to deal accurately and equitably with such a multitude of configurations will be difficult and as we have begun to see in a few instances—very controversial—much more so then even the present debate over rate structure.

The reason for this controversy over the meshing of dispersed solar systems with the utility system is quite simple. The individual consumer who installs a solar system becomes an autonomous, *unregulated* energy producer capable of delivering useable Btu for a variety of domestic purposes, There is no present method for the utility to forecast accurately or monitor the contribution from a multitude of individually unique, dispersed solar systems in its service area. If the introduction of such systems is stimulated by the passage of tax credits, as proposed in currently drafted federal legislation, the impact of solar energy upon a system could begin to become significant. It is at this point that a strategy for the utility's role regarding solar energy becomes critical. There are perhaps four possible strategies.

(1) Solar energy systems installed in the customer's property are solely a matter of concern to the builder or occupant (or both). The utility's responsibility ends at the meter and the utility will merely do its best to establish rates which are neutral regarding solar systems.

(2) The utility has determined that there is a "preferred" application for dispersed solar energy systems in its service area; e.g., solar heating of domestic water, solar-assisted heat pumps, etc. The utility would attempt to demonstrate that the widespread implementation of the "preferred" configuration would provide the most economically advantageous "total energy costs" to the consumer of its service area. Rate policies would be advocated and a public education and information program would be undertaken which would attempt to encourage adoption of the "preferred" configuration. Sizing of customer storage, attractive off-peak storage rates, and customer load management devices (or any of these) might accompany such a strategy.

(3) The utility would become actively engaged in the sale, installation, and financing of solar systems in its service area. The utility would perform technical analysis and provide certain warranties regarding system performance and reliability. Advantageous financing would be arranged with local lending institutions or provided by the utility directly. A variation might include leasing of solar systems. It is assumed that component equipment would be competitively acquired from manufacturers and that the actual installation would be performed by local contractors. For a rate-making point of view most of the financial impact to the utility would be "below the line."

(4) The most far-reaching solar strategy would be to treat the dispersed solar system installed in the customer's residence as utility property for rate-making purposes. Under this concept the cost of the Btu product in any individual's facility would be treated as a "supply" of usable energy to the entire service area just as if the Btu were produced at a central generating facility. The "cost" of the solar system would be "rolled in" and treated as a rate base investment. The property would be considered "used and useful" and depreciable for tax purposes.

The consumer would be billed on a basis of the Btu used. Centrally generated Btu delivered through the meter would be added to the Btu delivered by the solar system so that the customer would be billed for total Btu used.

Under this concept both the cost and benefits of the solar energy "generated" in the service area would be captured by *all* consumers. The utility would evaluate optimum configuration for dispersed systems and extent of implementation desirable in the service area on the basis of an economic comparison with other supplemental supply alternatives, such as new power plants or supplemental gas supply projects.

The unique feature of the pure rate base strategy is that it places the solar supply option on equal terms with other supply investments by the utility. The other three alternatives result in the consumer seeing the "average" cost of energy produced from the solar system. In an analysis where incrementally priced "solar Btu" are compared with average (rolled-in) price "conventional Btu" the solar energy will be at a comparative disadvantage. Under such circumstances competitiveness of solar energy will primarily be determined by the terms of financing for the installation and by the tax bracket of the user. These factors have little to do with the real energy comparison which should be made between competing sources of energy. Only a pure rate base approach results in an allocation of capital for new Btu on an equitable basis by allowing solar Btu to compete with conventional Btu at the margin.

Economics aside, there are several major legal and regulatory issues which a utility must consider if it wishes to contemplate a "rate base" approach. These include state regulatory statutes, federal antitrust laws, the Public Utility Holding Company Act, the Natural Gas Act, financing provisions, and tax aspects. I would like to touch briefly on the major points relating to each area.

STATE REGULATORY STATUTES

Within the state regulatory framework it must be established that the solar investment activity is a legitimate utility function. To accomplish this objective, the utility must prove that the solar investments are within the state statutes governing utilities. In a general sense, most statutes recognize the responsibility of the utility to provide efficient service and to avoid waste of energy. Many utility commissions have specifically approved the cost of solar activities, primarily for information dissemination and promotional activities, but in some instances involving utility loans or financial incentives.

While better energy utilization is arguably within the scope of the utilities' general responsibilities, the treatment of solar investments in rate setting is a somewhat different and specific matter.

Prior to embarking upon a solar investment program, it would be prudent for the utility to seek a declaratory ruling as to the includability of the activity in its rate calculations. Such advance approval should also outline the procedures for rate adjustment, the timing of rate hearings, and other specifics of the investment program. While allowable rates of return and other technical aspects of the rate-setting process might be subject to adjustment by further commissions, the fundamental concept of includability should not be subject to abrupt change.

In addition, it must be demonstrated that the investment in solar installations in its customers' facilities is not unjustly discriminatory. If it is contemplated that the solar installations would be provided to residential users, then it must be demonstrated that industrial and commercial users and residential users who do not receive the solar installation are not being treated in a prejudicial fasion. It would have to be proven that some benefits accrue to *all* customers. It will also have to be argued that the incremental fuel and capital savings which will be realized are greater than the "cost" of the solar investment. In making such a calculation, the price of incremental gas supplies or incremental electric generation capacity should be the basis for the analytical comparison.

The sharing of the gross benefits between the specific beneficiary and the overall system becomes a matter of establishing appropriate rates. The case for sharing of benefits due to incremental savings and costs due to solar-derived energy is not conceptually different from the issue of pricing incremental new supply sources in instances where such incremental supplies may substantially exceed current average prices. The doctrine of "rolled-in" pricing for different supply sources would apply to the solar supply components. It is therefore essential that the solar component be demonstrated to be beneficial to the system in terms of overall economics and supply security or reliability. Finally, the alleged environmental advantages of solar energy versus fossil or nuclear fuels must either be established through an explicitly legislated authority or by a regulatory interpretation which can substantiate the public benefits.

FEDERAL ANTITRUST LAW

Antitrust laws are complex and subject to varying judicial interpretation as the competitive structure of business is itself constantly changing. It can be argued that the action of a state regulatory commission could exempt the solar investment activity from antitrust laws. In an instance where the act—that is, the initiation of a solar investment program—is proposed by the utility and merely approved by the state regulatory authority, immunity from antitrust law is not automatically conveyed. A more defensible argument can probably be made on the basis that the utility is a purchaser of solar devices not a seller. Since antitrust law tends to be concerned mostly by actions among sellers which restrict competition, the proper structuring of the solar program is essential to the avoidance of antitrust problems.

The potential for violation of the Sherman Act is also very real since it could be charged that the utility was exercising monopolistic control over the purchase and installation of solar devices. Vendors or contractors whose products were not purchased by the utility might be effectively precluded from the market. A utility program could be designed to minimize these potentially monopolistic influences. For example, the selection of equipment would be based upon clearly publicized and technically substantiated performance specifications under competitive bidding procedures.

The utility would be precluded from installing the equipment with its own personnel or from owning any entity engaged in the production of equipment. Finally, wide discretion for equipment and installation should be provided to the home owner while the utility would set performance and quality control parameters for allowable system configurations so that "uneconomic" installations would be at the individual customer's discretion and expense. Furthermore, residential customers could either utilize a contractor and materials which would be arranged by the utility or the utility would offer to reimburse the customer for an installation which meets prescribed performance specifications.

Competitive bidding procedures by vendors and contractors should also avoid violation of restraint of trade and exclusive dealing provisions contained in the Sherman Act. While the utility purchase of solar equipment or installation services (or both) may serve to lower prices due to volume buying, this is a desirable aspect and seems to be within the scope of variance allowed by the Robinson-Patman Act.

PUBLIC UTILITY HOLDING COMPANY ACT

If the solar investment is undertaken directly by a utility it would not appear that such an activity would make the utility a holding company or remove any exemption which might already apply. Furthermore, a utility which is already subject to the act would seem to be exempted from any requirement of prior Securities and Exchange Commission approval since an exemption is granted for any acquisition of utility assets authorized by a state.

NATURAL GAS ACT

The Natural Gas Act grants the Federal Power Commission jurisdiction over the sale of natural gas for resale in interstate commerce and over the transportation of such gas. While the FPC has no direct jurisdiction over end-use gas distribution, it has influenced end-use distribution through its curtailment policies. The FPC's curtailment priorities and control over interstate pipelines are based upon end-use patterns, and the FPC has continuously urged state regulatory commissions to adopt compatible policies regarding distribution companies. As long as FPC allocation procedures utilize a fixed base period, the saving of gas by solar investment would allow a utility to serve more lower priority users or to increase the number of high-priority users. The reallocation of gas from utilities engaged in an aggressive solar investment program would penalize the utility and its customers. This problem of conflicting federal policies is inherent in the present framework where utilities are fearful that any "self-help" project involving high-priced incremental supplies, successful conservation, or a solar augment would only result in the reallocation of cheap, traditional sources to systems unwilling to undertake self-help investments. The Emergency Natural Gas Act of 1977 established reallocation authorities in emergency conditions and provided some compensation provisions to mitigate the financial consequences on reallocation. But it is clear that a more comprehensive policy regarding the impact of conservation and solar activities on gas supplies would be beneficial.

FINANCING

Many mortgage bond indentures require that the funds be used only to acquire property which can be placed under the lien of the indenture. While the solar collector could be viewed as removable property, much of the installation would involve modification to the customers' facility and heating-cooling system and thus be viewed as fixtures. As a consequence, it may be necessary to finance such a program through some form of supplementary financing which might involve subordinated debentures or subsidiary financing.

DEPRECIATION

The treatment of the solar investment for tax purposes is an important feature of determining economic feasibility. If it can be demonstrated that the investment is utility property, then it would seem that certain tax advantages such as accelerated depreciation and tax credits could be available. The inclusion of fixtures within a customer's residence to facilitate the delivery of a utility service has precedence in the case of telephone lines and gas feeder lines. Rather than guess on the outcome of this issue, a ruling should be sought from the Internal Revenue Service and state regulatory commission as to eligibility depreciable life and other aspects.

In conclusion, I believe that for a rate base approach to be successful, it will require full public policy support. Currently pending legislation clearly does not contemplate such an approach, but the extent of market penetration and consumer satisfaction resulting from a tax credit program may turn out to be disappointing. If this occurs and if the need for a massive and rapid solar effort becomes critical, a utility rate base approach may turn out to be the most equitable and effective method.

COGENERATION AND WASTE HEAT—I

(By Alvin Kaufman and Barbara Daly)

A major possibility for reducing the need for more central station electric power generating facilities is the development of facilities that produce industrial process heat and electricity. The next selection discusses the technology of this type of system and analyses the barriers that face its widespread use. It concludes that utilities are unlikely to build many dual-purpose facilities, but that industrial users may find economic and technical advantages to producing on-site steam and electricity if some institutional barriers are eased.

Some of the discussion about rates and interrelationships between cogenerators and utilities should be updated in light of the recently passed National Energy Act, which includes a section dealing with this problem. Under the new legislalion, utilities are required to sell back-up power and purchase excess power from cogenerators at equitable rates, as determined by regulations to be formulated by the Federal Energy Regulatory Commission.

COGENERATION—PROBLEMS AND OUTLOOK

(By Alvin Kaufman, Senior Specialist in Business Economics (Resources and Regulation) and Barbara Daly, Research Assistant, Senior Specialists Division—Oct. 5, 1977)

SUMMARY

Cogeneration is the production of both steam and electricity from a single heat source. It is technically possible because a single purpose electric generating plant uses only one-third of the heat input and vents the remainder to the atmosphere. Process heat plants tend to have a somewhat higher efficiency. Cogeneration permits utilization of this waste heat through use of three basic boiler-turbine combinations. These include the back-pressure steam turbine, the extraction steam turbine and the gas turbine-waste heat boiler. The extraction turbine is usually used at utility plants and the back pressure or combined cycle units at industrial plants.

Cogeneration is said to reduce the cost of electricity as well as the use of fuel, save capital, reduce cooling water needs, add flexibility to power plant siting and permit easier adjustment of supply to demand. Not all industrial steam plants can be converted to cogeneration, nor can utility plants be converted to service all industrial steam loads. In any case, cogeneration potential is estimated to range between 33,000 MW to 76,000 MW by 1985. Cogeneration would result in capital savings ranging between $16 billion and $24 billion plus fuel savings on the order of 600,000 to 700,000 barrels per day of oil equivalent.

Despite its advantages, however, cogeneration has some technical problems, although the major difficulty appears to be institutional. For example, is cogenerated steam and electricity going to be regulated, and if so who will do the regulating—the Federal or State government?

Cogeneration will not be the panacea seen by some although it will contribute to the nation's conservation effort. Our current reading of the prospects are that dual facilities on the utility level, at least through 1985, will have relatively modest growth because of the difficulty of finding sites suitable for both utility and industrial plant use that are close enough to permit transmission of the steam without undue economic losses. The major thrust in cogeneration will, it appears, come for industrial plants with most of these sized to produce the electric or steam needs of the plant itself and generally not producing electricity for resale. The latter appears to be the case because most businesses will probably attempt to avoid coming under the regulatory authority of either State or Federal Government for the sale of excess electricity. Working against this will be the need for such plants to purchase back-up electricity at reasonable rates because of the mismatch between steam and electricity production. The authors generally conclude that cogeneration will still face a long uphill battle, although the downward trend in development of this concept will probably be reversed.

INTRODUCTION

As a consequence of national security, economic, and environmental imperatives, there is currently underway an intense effort to foster energy conservation. An important part of this effort is the recovery of waste heat normally rejected by electric and steam generating plants to the atmosphere. This is not a new concept in that cogenerated energy in 1950 accounted for 17 percent of the U.S. total, but had declined to 4 percent by 1974.[1] The drop occurred as a result of changing economic conditions. For example, electric costs from central generating plants were declining during the period, making purchased electricity cheaper than cogeneration. This competitive advantage was compounded by a continuing shortage of the most commonly used fuel, natural gas. In addition, some states have rules and regulations which tend to discourage electric generation by anyone other than a franchised utility. Further, some utilities have rate schedules that make it uneconomic to use the utilitiy as a standby source of backup power for industrial use. In recent years, however, as electric and fuel costs have increased there has been a renewed interest in the cogeneration of electricity and steam, either from central electric plants or from industrial steam plants.

There are those who feel cogeneration can make a very substantial contribution to the solution of our energy problem, and those who feel the contribution will be minor. In an effort to place this matter into perspective, and in order to provide the Congress with the necessary background, we have prepared this paper. We will first review, in a nontechnical fashion, the various methods that can be used to produce both electricity and steam, the possible savings that might accrue, and then discuss the technical, economic and institutional problems.

It should be noted that cogeneration is a part of the much larger subject of waste heat utilization. It is our intent, in this paper, to deal only with cogeneration.

BACKGROUND[2]

Cogeneration, as indicated above, is the production of both steam and electricity from a single heat source. This can be accomplished either with steam as the primary product and electricity the byproduct or vice versa. Cogeneration is possible because only one-third of the heat input to a single purpose power plant is used; the remainder is vented to the atmosphere. In the congeneration mode some of this waste heat is used to produce another product. To accomplish this, three basic boiler turbine combinations can be used. These include the:

(1) back-pressure steam turbine, (2) extraction steam turbine, and (3) a gas turbine-waste heat boiler. These can be of various sizes and can be modified to change the output mix of electric power and steam yielded by the plant.

In back-pressure steam turbines, high pressure steam, generally ranging between 600 to 2400 pounds per square inch (psi) is used to rotate a turbine, which in turn operates an electric generator. The steam is discharged from the last stage of the turbine at relatively low pressures, generally 50 to 150 psi. This steam is usually suitable for industrial process use.

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[1] Kirschten, J. D., "The Cogeneration Movement Is Picking Up Some Steam," National Journal, Jan. 5, 1977, p. 103.

[2] This material is based on Federal Energy Administration, "Electric Utility Rate Design Proposals," Interim Report. February 1977, FEA/D-77/063, pp. 170–174.

The extraction steam turbine operates in a similar manner, except that the steam is extracted from intermediate stages of the turbine for use in industrial processes. As a result, the need for various temperatures and pressures can be accommodated. The exhaust from the turbine is condensed and returned to the boiler for reuse as in a single purpose power plant.

The gas turbine-waste heat boiler tends to be a somewhat different kind of animal. It is also often called a combined cycle unit. In this particular mode, a combustion turbine is fired using either a compressed air-natural gas mixture or a compressed air-distillate petroleum mixture. The hot combustion gases are used to propel the turbine and an electric generator just as in the case of a steam driven turbine. The exhaust gases, however, tend to be rather hot, and can be passed through a waste heat steam boiler for recovery of that heat as steam at pressures up to 1000 psi.

Cogeneration techniques can be applied at either central electric generating stations or at industrial plants producing process heat for their own use.

As a general rule, extraction steam turbines are used for cogeneration at utility power plants since they produce a high proportion of electricity relative to steam. Industrial cogeneration plants often use the back pressure steam turbine or the combined cycle unit because of the higher proportion of steam produced.

Approximately 30 percent of the steam produced by industry for process heat is also used for electric power generation, but only a very minor portion of electric utility steam is used for cogeneration. The four major examples of the latter are Gulf States Utilities Co., Public Service Electric and Gas Co. of New Jersey, Public Service of Indiana, and Consumers Power Co.[3]

The oldest dual purpose plant is Louisiana Station No. 1 of Gulf States Utilities Company, located in the North Baton Rouge industrial area. The plant was completed in 1930 and has been expanded several times since then so that total steam generation is 5 million pounds per hour with electric generating capacity at 240 megawatts. Steam is currently supplied to the Ethyl Corporation (0.4 million lbs/hr) and to the Exxon Corporation (2.4 m lbs/hr). The steam load is firm, although Gulf States has the right to reduce the supply in case of an emergency, and the customers can reduce demand. Fuel is supplied by the customers. The sale of steam is considered, under a 1952 decision of the Louisiana Supreme Court, to be exempt from the usual utility regulation.

Public Service Electric and Gas Company of New Jersey began selling steam from its Linden Station to an Exxon Refinery in 1957. Somewhere between 1 and 2 million pounds per hour are transmitted over a distance of 6,300 feet. As a consequence of fear of oil contamination, raw water is returned to the plant instead of condensate. Fuel is supplied by the customer. Steam sales in this case, are not regulated by the Public Utility Commission.

Public Service of Indiana modified its Cayuga plant in 1975 to produce 225 thousand pounds per hour of steam at an incremental cost of $2.6 million (1973). The steam is delivered to Inland Container

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[3] Dow Chemical Co., "Energy Industrial Center Study," National Science Foundation, June 1975, PB-243, 823, pp. 100–102.

Corporation through a 9,000-foot steam line. No condensate is returned.

The first dual-purpose nuclear facility is being built by Consumers Power Co. at Midland, Michigan. Of the 1,300-MW capacity of the plant, some 500 MW will supply approximately 4 million lbs per hour of steam to Dow Chemical Co. This plant is currently involved in considerable controversy and its future is unclear.

THE PROS AND CONS

Cogeneration is said to reduce electricity costs and the use of scarce fuels, save capital, reduce cooling water requirements, add flexibility to power plant siting, and permit easier adjustment of electricity supply to demand.[4] This last is particularly important because of uncertainty in regard to future demand; current estimates range between 1–2 percent annual growth up to more than 7 percent.

Over the last 20 years, however, the relatively inexpensive gas and oil-fired package boiler producing low pressure steam, coupled to economies of scale accruing from large electric generating units, have acted to shift steam operations to industry and electric power generation to the utilities. To reverse this tide will be difficult because many of the package boilers used by industry are unsuitable for cogeneration, and many of the utility plants will be costly to convert.

An industrial plant using at least 400,000 pounds of steam per hour is needed to justify by-product power generation. Such plants only comprise about 40 percent of the industrial steam load. Despite this, the installation of by-product power generation for these larger plants has the potential for some 33,000 megawatts of electric capacity by 1985 with an additional 38,000 megawatts possible through the addition of condensing capacity.

Conversion of these plants would require investment of $19 billion by 1985 but would relieve the utilities of $38 billion in investment, thus resulting in a $19 billion net capital saving. In addition, an estimated 680,000 barrels of oil equivalent could be saved each day by 1985.[5]

Dual purpose plants, on the other hand, require a steam load at one location of at least 1 million pounds per hour. Capital savings in this instance would be relatively minor if not actually negative. This occurs because of the need to protect the quality of the boiler feed water. In the case of a fossil-fired plant, condensate returned from the industrial steam customer would not be suitable for introduction into a high-pressure boiler due to the fear of corrosion. As a consequence, a large, elaborate water treatment plant for the feed-water make-up would be required.

In the case of nuclear units, three separate steam loops joined by two heat exchangers would be required to prevent radioactive contamination of the process steam.[6]

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[4] Williams, Robert, H.; "The Potential for Electricity Generation As A Byproduct of Industrial Steam Production in New Jersey" Center for Environmental Studies, Princeton University, June 21, 1976. PU/CES–#31.

[5] Spencer, R. W., W. S. Butler, M. K. Enns, and B. W. Wilkinson; "The Potential for Fuel Economies via Combined Steam-Power Production.[1] Energy Systems and Policy. Vol. 2, No. 1, 1977. pp. 59–84.

[6] Dow op. cit., p. 102.

The savings from by-product and dual purpose plants are not additive because both depend on the same industrial steam base. If by 1985, industry generated 238 billion kwh for its own use plus 101 billion kwh for sale to utilities, but purchased 600 million pounds of steam per hour from the utilities, a net reduction of $16 billion in investment is postulated, with fuel savings in excess of 700,000 barrels of oil equivalent per day.

The Dow study postulated four cases: A. Industrial generation for use; B. Industrial generation for both use and resale; C. Joint venture dual purpose central power station; D. Industrial power and dual purpose plants. Under these four cases, the capital savings varied from $2 billion annually in A to $5 billion in D. Utility customer savings were computed as 0.7 percent in A; 2.9 percent B; 6 percent C; and 5 percent D. The low savings for Case A result from the fact most of these are kept by the industrial generator and very little is passed on to other customers except as a kind of spill over.

Estimates of energy and capital savings tend to vary, however, depending on the assumptions. Another study indicates that the actual penetration of cogeneration into the market will depend on distribution of plant size, degree of plant utilization, mix of steam, gas and diesel cogeneration systems, and the degree of economic and regulatory stimulus provided by governmental action. If things continue as at present, it is projected that cogeneration capacity will rise from 11,000 megawatts to approximately 18,000 megawatts by 1985–87. If various economic incentives are instituted, these figures should increase to range somewhere between 37,000 and 61,000 megawatts. In the event that mandatory and/or tax measures designed to equalize the return on investment criteria for cogeneration are instituted, the level of cogeneration could reach 76,000 megawatts. This study indicates that at the 61,000 megawatt level (a 50,000–MW increment) the additional fuel savings would be 588,000 barrels per day oil equivalent. The capital cost for 50,000 megawatts of cogeneration incremental capacity, including investment and fuel supply facilities, would be $39.5 billion, approximately $24 billion less than the cost of generating plant and fuel supply facilities for conventional capacity.[7]

Despite the above estimates there is an ongoing debate as to the relative importance of cogeneration as an energy source. This is illustrated by the recent situation in the State of New Jersey.

The New Jersey Public Interest Research Group (PIRG), a Ralph Nader inspired organization, recently reported there are some 186 industrial sites in New Jersey that could support 5,250 MW of gas turbine cogeneration. Applying a capacity factor of 70 percent to cogeneration and 50 percent to nuclear plants, the study calculated this cogeneration capacity could head off the construction of some 6,200 MW of nuclear plant construction.

In contrast, Public Service Electric and Gas (PSE&G), the electric utility which serves most of the industrial sector of the state, finds in its service area a cogeneration potential of only 430 MW and indicates this may be a high estimate rather than low. PSE&G further reports that the cogeneration potential would only serve to postpone needed nuclear capacity by a year or two, and due to rising construction costs may result in an economic penalty. The study also states "Cogeneration would significantly increase America's dependence on oil which is currently counter to national policy." [8]

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[7] Widmer, T. F. and Dr. George N. Hatsopoulos; "Summary Assessment of Electricity Cogeneration in Industry." Thermo Electron Corporation, Mar. 15, 1977.

On balance, it would appear that the major advantage of cogeneration is the energy savings. Thus even if the ability to apply the concept is relatively limited there are benefits from using it where economically feasible.

PROBLEMS IN IMPLEMENTATION

The Dow study referenced earlier indicated the major problems in by-product cogeneration were availability of equipment and suitable coal, air quality standards, sulfur removal technology, company investment criteria, a shortage of trained personnel, and the attitudes and policies of utility and industry managements.

In the latter case, there may be a reluctance to buy back excess electricity on the part of the utility for a variety of reasons related to operations. These objections can probably be overcome by careful planning aimed at integrating industrial generation into the utility system.

The principle requirement is for predictability of the industrial generation to allow for rational planning and operation of the utility system. Most utilities would probably want to have the power-generating units under their direct control, although not necessarily their ownership. These units could then be operated at a fixed output or possibly through some kind of automatic generating control. In any case, operations would have to be scheduled just as the utility would schedule the operation of their own units for a given day. Operating controls would also probably incorporate load schedules, voltage and reactive currents carried, regular maintenance schedules, the specification of settings for protective relays, arrestors, and grounding equipment, and finally the uniform tagging of lines and equipment in order to assure the safety of personnel while attempting to isolate trouble.

The sale of electricity to the utility in most cases will probably not be a problem since electric power generation will generally not exceed the needs of the plant, and often may be less. This latter point may pose a more serious barrier in the sense that utilities generally charge industrial-commercial customers for the energy they use and the capacity required to satisfy their demand. Thus demand charges tend to reflect the relationship between the customer's total use of electricity and his peak use (load factor). Inasmuch as a major portion, if not all, of the cogenerator's base load will be supplied by his own plant, while his peak needs will probably come from the utility, demand charges levied against him are likely to be relatively high, possibly creating an economic disincentive. Mandating a reduction in such charges will result in shifting the cost of utility supplied peak load facilities for cogeneration to the general ratepayer. The latter, however, might still benefit since less base load capacity would have to be paid for. Base load units are generally more costly to build than peak load, but are less costly to operate.

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[8] Electrical Week, Mar. 21, 1977 "Cogeneration Fuss in New Jersey: PIRG Sees 5,250MW Potential; PSE&G, 430MW", p. 5–6.

Problem areas for central station cogeneration are noted as the method and cost of replacing steam condensate (discussed above), the cost and energy losses from long steam lines, a lack of space at sites, and the lack of capital savings.

Environmental problems would have to be assessed for each plant on an individual basis. The higher efficiency, however, should result in reduced air pollutant emissions, and in thermal discharges from cogenerating plants.

Institutional Problems.—The major disincentive to development of cogeneration, however, appears to be institutional barriers. Testimony before the Subcommittee on Energy and Power, House Interstate and Foreign Commerce Committee, on April 9, 1976, indicates one of the main hindrances to greater development is confusion over regulatory authority. That is, under whose jurisdiction would steam and electric sales fall; State, Federal or both. That record also indicates that there is a desire not to get involved with FPC regulatory requirements, including the authority to prohibit issuance of securities, rate regulation on interstate or wholesale sales, oversight of depreciation techniques, reporting requirements and regulatory fees, etc. There is also confusion as to whether waste-heat utilization projects involving several partners would classify as a holding company, and thus be subject to registration with the Securities and Exchange Commission under the Public Utility Holding Company Act of 1935. Another difficulty is the legal provision in many States prohibiting the sales of electricity by any one other than a franchised public utility. Such a provision inhibits development of cogeneration by making it legally difficult for a cogenerator to sell excess electricity from his units. As the preceding material indicates, many of the regulatory problems revolve around utility vs. industrial ownership arrangements. The Princeton report cited previously outlines the alternative positions as follows: [9]

"*In favor of utility ownership*

"(1) With cogeneration units in the rate base utilities should have a more positive attitude toward cogeneration.

"(2) Utilities better understand how to operate and maintain power generating systems, so that industrial 'learning problems' with regard to power plant operations would be avoided.

"(3) Owning the plants, the utilities could more easily control their output and thereby better balance supply and demand for the utility system.

"(4) Because regulated utilities are assured a fair rate of return on their investments, they are willing to accept a rate of return lower than private industry, thereby making industrial byproduct power cheaper.

"(5) An industrial firm may be detered from owning a cogeneration unit capable of exporting power by the prospect of being encumbered by utility regulations.

"*In favor of industrial ownership*

"(1) Problems of coordinating utility and industrial activities would probably be less.

"(2) Scrutiny of rate negotiations between a utility and many industrial producers should give the Public Utility Commission a better data base for establishing utility rates for all customers."

There are several minor discrepancies in the above quotation. First, utilities are not assured a fair rate of return, but are simply permitted to earn a given rate of return if they can. As a general rule when costs are declining the utility will earn more than permitted; when costs are rising they will earn less.

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[9] Williams, op. cit., pp. 25–26.

Item 2 in favor of industrial ownership also appears to be a non-advantage. Utility Commissions have full access, in most cases, to the books of the utility. Further, in most utility rate cases voluminous cost data is filed for consideration of the Commission. It is unlikely that scrutiny of cogeneration data would add very much. Further, cogeneration plants will tend to be smaller and may have a somewhat different cost distribution.

It is also unlikely that the additional facilities required for dual purpose plants will be included in the rate base. In many instances the steam sale will be excluded from regulation and thus the equipment used in that end of the business would also be excluded from regulated rates

THE OUTLOOK

Cogeneration has many advantages in terms of cost and energy savings, but it also has limitations as discussed above. These encompass technical, economic, and institutional problems. In an effort to minimize some of these several bills have been introduced in the 95th Congress. These include a proposal by the President (H.R. 8444), as well as identical bills by Senator Hart and Representative Ottinger (S. 1363 and H. R. 6661), and Senator Durkin (S. 5904). Most of these bills tend to be similar in that they provide a 10 percent additional investment tax credit for cogeneration equipment, and strive to assure that utilities will provide backup service and will buy surplus electricity.

The Hart-Ottinger bill also requires a series of comprehensive policy studies.

Despite these efforts to clear the way for cogeneration, development of this energy mode, while contributing to the nation's conservation effort, will not be the panacea seen by some. Our current reading of the prospects indicate that cogeneration efforts by ultilities, at least thru 1985, will be relatively modest. This is because of the difficulty of finding sites suitable for both utility and industrial plants that are close enough to permit transmission of the steam without uneconomic losses. Further, since there is no capital saving in this mode of operation, unless there is some other economic advantage, there is little incentive for the utility to undertake cogeneration.

It appears to us that the major thrust in cogeneration may be by industrial plants but most of these will be sized to produce the steam needs and most of the electric requirements of the cogenerator. As a general matter, cogenerators will not produce electricity for resale in our opinion. In most cases it will not be the price, but the regulatory jungle that will scare off efforts by cogenerators to sell electricity to the grid. The incentive to produce electricity for plant use will come from rising industrial electric rates compounded by "lifeline" and other social subsidy arrangements. The push to use coal with the resulting need for stockpiles, conveyor belts, and stack gas cleaning equipment might inhibit what we perceive to be a push toward cogeneration. The latter may eventually be solved through use of fluidized bed burning and solvent refined coal.

Cogeneration, while a worthy concept, still faces a long, uphill battle although the downward trend will probably be reversed.

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COGENERATION AND WASTE HEAT—II—NOT MAN APART

This article is a report of a study by Robert Williams discusing the potential for industrial cogeneration of electricity and process heat. Like Kaufman and Daly in the previous study, Williams reportedly considers institutions the most important barriers to achievement of full utilization of the cogeneration option, which he sets at 208,000 megawatts in the year 2000.

[From No Man Apart—Mid September/October 1978]

Hot Prospects for Reusing Heat, Steam

"Cogeneration . . . may well provide about as much new net electricity as the US economy would need by 2000," beyond current plants, replacements, and units under construction, concludes physicist Robert Williams in an 84-page report slated for publication in Annual Reviews of Energy. Williams defines cogeneration as electricity generation in factories, a byproduct of process heat or steam, and estimates the year-2000 potential at 208 gigawatts of equivalent capacity. Well above the current US capacity of 15 GWe, Williams's estimate is also well below the maximum thermodynamic potential of 1000 GWe—theoretically obtainable by associating diesel engines with all industrial process steam use. The current (12/1977) installed capacity of the US electric utility industry is, for comparison, 557 gigawatts.

Williams believes the principal obstacles to deployment are institutional, not economic. He sees utility resistance as the biggest obstacle, "manifest in extraordinarily high rates charged by the utility for back-up power and in extraordinarily low rates offered to industrial firms for power generated in excess of onsite needs." Other obstacles include national fuel strategy (coal conversions and cogeneration policy are not pursued simultaneously), average cost decision making, and the national problem of excess utility capacity.

At one time, cogeneration represented a large fraction of the total electricity produced in the United States. In many countries, particularly in Western Europe and Scandanavia, it still does. But US cogeneration has declined from 22 percent of total electric sales in 1920 to 18 percent in 1940, to 9 percent in 1960, and to a low of 4 percent in 1976. Largely responsible was "a long term trend toward ever lower prices for electricity generated at central station power plants."

At the same time, utilities have not compensated cogenerators fairly. "If an industrial firm wishes to cogenerate its own electricity and rely on the utility for the backup supply, the standby charges imposed by the utility today for this backup service would usually be at least double the average price the industrial firm pays for electricity. In addition, utilities have usually been unwilling to pay a fair price for electricity generated in excess of onsite needs. Typically, because an industrial owned cogeneration unit is not in the utility's rate base, the highest price a utility is willing to pay is a price equal to what it would cost the utility for just the fuel to produce the same amount of electricity. At such a price it is often not profitable for the industrial firm to generate excess electricity."

These policies may now be outmoded. After at least 35 years of declining real prices for electric power, prices began, in 1970, to rise faster than general inflation rates. "Traditional opportunities for cost cutting in power generation are being exhausted," notes Williams.

"Thermal efficiencies of central electric power plants haven't increased since about 1960, following a 60-year period during which the average efficiency increased eight-fold, and the emphasis since about 1960 on cost cutting through the pursuit of economies of scale seems to have run its course."

Cogeneration has regained a competitive edge over other forms of central station generation, Williams argues, "so that if the institutional obstacles are eliminated that now discourage the evaluation of cogeneration projects on the basis of a comparison of long run incremental costs, cogeneration could become the major source of new power generating capacity in the US in the last ten to 15 years of this century."

Of four studies to date on near term cogeneration potential, Williams feels that none sufficiently analyzes the excess capacity problem. The four studies (Dow Chemical for National Science Foundation, Thermo Electron for the Federal Energy Administration, and two by Resource Planning Associates for FEA and for the Energy Research and Development Administration) estimate, under widely varying technical and economic assumptions, a 1985 potential of 20 to 260 gigawatts of equivalent capacity.

Williams believes that the estimates in all four studies are low. The true economic estimates would be much higher, he thinks, but the "actual pace of development of cogeneration in the period up to 1985 will be slower than economic considerations alone would indicate, because for a number of years utilities in many parts of the country will not have a strong interest in accepting excess cogenerated electricity into the utility grid or in utility ownership of cogeneration facilities, simply because there will not be a significant need for new electrical generating capacity in most areas—a factor not considered in any of the cogeneration analyses discussed here."

Current (12/1977) installed capacity in the US is about 557 GWe and rising at 5 to 6 percent per annum. As Williams notes, about 275 GWe of new central station facilities are under construction and scheduled for operation by 1986. Data from Edision Electric Institute show that non-coincident peak demand in the US last year was 396 GWe, for a gross peak margin of about 41 percent, at least 20 percent more than is needed on any individual system and worse than the margin Williams cites with 1976 data. At the same time capacity is growing at 6 percent per year, demand is slowing to about 3 percent per year. Since 1973, the average annual increase in kilowatt-hour sales has been 3.3 percent (peak growth is about the same). This year, with high economic growth in the first half of the year, electricity production is up 2.3 percent over a similar period last year. The overcapacity problem is worsening. Williams does not believe it will abate until 1985 and, at that point, cogeneration will be the major new source of power.

While this argument is persuasive, this reporter (JH) finds the conclusion overstated, Projected capacity for 1986 is extremely labile, and can be altered to suit changed circumstances. Of the 273 gigawatts estimated for construction, 145 are relatively short lead-time fossil steam plants. It would not be difficult to convert some of the contracts for these plants into contracts for gas or steam turbines for cogeneration. Indeed it is not difficult to do that for nuclear facilities; the vendors don't change.

Second, Williams calculates, in an excellent economic analysis, that cogeneration can be competitive under some conditions with existing capacity. Any increase in fuel costs would make it more so. Thus cogeneration could be a major alternative for the replacements market, or for a new premature retirements market. In the latter case, the 4000 or so BTU/kWhe difference in efficiency between existing central station fossil plants and new cogeneration facilities could outweigh the cost of cogeneration capacity.

Third, existing tax law in the United States makes it very difficult for utilities to stop spending money, even when demand is slack. Investment tax credits and accelerated depreciation postpone, but do not eliminate entirely, the tax burden on a utility. If investments aren't made, taxes bite heavily. All these factors bear consideration when analyzing cogeneration's near term potential.

In general, Williams' economic analysis is quite conservative. In 1976, the generation of a kilowatt-hour of electricity for industry cost utilities 12.4 mills (1.2 cents). Delivered, this electricity costs 20.7 mills, well under the 1977 industrial rate (all, 76 dollars) of 23.7 mills or the average customer rate of 32.3 mills. Williams figures the cost of a new (bought today, on-line tomorrow) nuclear plant at 22.4 mills per kWh sent out and 31.3 mills/kWh delivered. This conservative estimate is well below many others; California Energy Commission estimates are about 65 mills/kWh. Williams finds cogeneration competes with any of these estimates. In his worst case, a 5 MWe steam turbine delivers electricity for 23.7–34.0 mills/kWh; while in the best case a 30 megawatt steam turbine delivers electricity for 18.6–24.7 mills/kWh.

Williams makes other conservative assumptions. Any backup costs for cogeneration are at the marginal nuclear rate (31.3 mills/kWh). Real fossil fuel costs are assumed to double over the life of the cogeneration plant. Marginal transmission costs are assumed to be shared by the utility and industry. The capital cost of the facilities is shared between steam and electricity (low values) or is assigned entirely to electricity production (high values). Nuclear capital costs are estimated at $800 per kilowatt, while oil-fired gas turbines range from $290–470/kWe and coal steam turbines range from $860–1475/kWe. Both cost less if shared.

Technological choice and fuel policy will play an important role in achieving cogeneration's potential, says Williams. The US coal conversion policy encouraging a shift from oil to coal will force retirement of existing boilers and construction of new coal boilers, stimulating cogeneration. At the same time, Williams believes utility resistance to cogeneration coupled with the overcapacity problem will seriously discourage industries from installing needed cogeneration equipment when they make conversions to coal. If industries, on the other hand, install cogeneration equipment now, they will probably choose steam turbines, the least productive cogeneration technology.

Atmospheric pressure fluid beds (AFB), Williams says, will be routinely available by 1979. "It is noteworthy that strict enforcement of the federal standards for sulfur oxide emissions would help the market development for fluidized bed technology, simply because sulfur oxide control via fluidized bed combustion may well prove to be less costly that sulfur oxide control via stack gas cleanup technology. [An Exxon study estimates that the coal fluid bed market would be diminished by a third if states with standards more permissive than the federal government's standards are allowed to keep them.] This is a good example of how a strong commitment to environmental protection can spur technological innovation."

AFB units could save large amounts of fuel with closed-cycle gas turbines, such as have been used in West Germany. Pressurized units could use gas turbines directly and may be available as soon as atmospheric units.

But Williams feels utilities will be uninterested in cogeneration capacity as long as the over-capacity problem persists. To discourage over-building, Williams suggests not including the cost of unneeded plants in a utility's rate base, or making the rate of return on rate base a function of reserve margin, with utilities penalized for over- and under-building. (A further incentive to cogeneration might be to exclude unforeseen construction costs from a utility's rate base, or to penalize it through rate of return adjustments for failing to estimate construction costs accurately.)

Williams bases his estimate of 208 gigawatts for year 2000, finally, on a number of conservative assumptions. He estimates that boiler fuel consumption will rise at 2 percent per year to 2000. The studies noted earlier gave a similar figure for 1985 steam loads, but gave insufficient credit to conservation. Believing that small scale is not an obstacle to economic potential, Williams uses Dow's estimate that "it would be practical to associate 50 percent of all process steam production with cogeneration capacity." At a reasonable 90 percent capacity factor for industrial sites, this would mean that 45 percent of the industrial steam load would be associated with electricity production. (This is not an absolute capacity factor; rather it is the capacity factor of the turbine during the time steam is produced.) Of this capacity, Williams estimates 20 percent is coal-fired steam turbines, 15 percent is coal fluid beds with gas or gas-steam turbines, 5 percent is oil-fired gas or gas-steam turbines, and 5 percent is oil-fired diesels. The fluid bed estimate, Williams finds, is consistent with an Exxon estimate of market potential in the year 2000 with existing industries. Additionally, following the Exxon report, Williams adds fluidized beds in synthetic fuel and coal beneficiation plants. This total of 208 gigawatts of equivalent capacity would save about 5 quads of energy over what would be required if the same amount of electricity were produced at new central station thermal-electric plants.

COGENERATION AND WASTE HEAT—III

(By Carl E. Behrens)

The next selection was prepared for a workshop on the utilization of low-grade waste heat from power plants. The specific topic, legislation, was quickly exhausted, and most of the presentation was devoted to the role of electricity in the National Energy Plan. However, some discussion of the possibilities of district heating with hot water from power plants is included, including the institutional relationships between utilities and their prospective consumers and the role of Government in commercializing the technology.

LEGISLATION AFFECTING WASTE HEAT UTILIZATION [1]

(By Carl E. Behrens)

INTRODUCTION

The topic of legislation affecting power plant waste heat utilization is not one which will take long to exhaust, from the positive sense. Although some Congressional initiatives have been made in the area, on the whole relatively little attention has been paid to the subject. Most references to waste heat utilization treat it as the lesser part of "Cogeneration and . . ." For instance, the bill introduced by Mr. Hart and Mr. Sasser in the First Session of the 95th Congress was titled the Cogeneration and Waste Heat Utilization Act, and the only part of that legislation that survived was the section of the Utility Regulation portion of the National Energy Act that directed the Federal Energy Regulatory Commission to develop regulations for the integration of industrial cogeneration facilities with regulated utility systems—which is generally irrelevant to our topic here. Another portion of the National Energy Act includes waste heat utilization equipment among the items that are eligible for an additional 10 percent investment tax credit.

There are several programs in the Department of Energy budget dealing with various projects in utilization of waste heat from electric power plants. The level of funding, however, is quite low, and it is difficult to find these programs in the maze of budgetary ebb and flow that typifies Government energy activity in recent years.

Part of this difficulty no doubt derives from the reorganization of energy functions in the new Department of Energy. Over and above this, however, lies a suspicion that it indicates a general lack of interest in waste heat utilization. For the Administration's energy policy makers, and to a large extent for the Congress, cogeneration and waste heat utilization are part of "energy conservation"—and, in the case of our topic here, a very small part.

THE NATIONAL ENERGY PLAN

Since this attitude of comparative lack of interest arises out of the peculiarities of the National Energy Plan, as formulated by the Administration, a brief review of that proposal will be useful.

The main thrust of the NEP—the "overriding objective"—is the need to reduce dependence on foreign oil in the face of shrinking domestic sources of oil and natural gas. The "cornerstone" of the efforts to reach this goal is conservation, not only of oil and gas, but of all forms of fuel and energy.

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[1] Prepared for the Atlanta Workshop on Factors Affecting Power Plant Waste Heat Utilization, November 1978.

In addition to conservation, the substitution of abundant fuels for scarce oil and natural gas is part of the NEP. However, because of the President's view of uranium and nuclear energy as a "last resort", the abundant substitute consists almost exclusively of coal.

A third feature of the NEP is the development of "renewable" energy sources for the long term. This comes down largely to solar energy.

THE ROLE OF ELECTRICITY

Within this model, electricity has an equivocal role. At first view, it would appear that electricity, if derived from sources other than oil or natural gas, could substitute for those fuels. Thus, vigorous programs—for example, to develop electric vehicles for transportation, where oil supplies all but a negligible fraction of energy consumption; electric heat pumps and other electric devices in the residential and commercial sector; and cogeneration of electricity from process heat systems for industry, where economically practical—would seem to be indicated.

However, in the view of the NEP, electricity has serious drawbacks. It is seen to be wasteful of fuels, in that two-thirds of their heat goes up the stack or out the cooling tower. This factor, of course, is meaningless in the case of hydro power and is unimportant in the case of uranium, which has no other use at present than the generation of electricity; but, as noted, nuclear power is considered undesirable for other reasons, and large hydroelectric sites appear to be few.

In addition, electricity is viewed as a major competitor to solar heating and cooling, which are seen to be on the threshold of commercial viability. Thus a vigorous, economically healthy electric power industry that is expanding and trying to sell large amounts of relatively cheap power to any customer who will buy—obviously not its conditions at present—would be a powerful obstacle to the development of solar energy now and into the next century. So the solution is to deemphasize electricity. Carried to an extreme, this view calls for an immediate start on dismantling the central electric power system, on the grounds that as long as it remains in place, the economic advantage of its existing distribution network will make decentralized solar power uneconomic. The NEP does not go this far—as evidenced by the excoriating attack by Barry Commoner published in the Washington Post shortly after the plan was announced. Under the title, "The Hidden Jokers in Carter's Energy Plan", Commoner accused the administration of committing the nation to commercialization of breeder reactors, because it countenanced the continued use of nuclear power, thus allowing the electric industry to expand at the expense of solar power. Nevertheless, the consciousness of competition between central electric power generation and decentralized solar power is clearly present in the thinking of the Administration's energy planners.

SECONDARY STRATEGIES

From these major NEP policies, a number of secondary strategies emerge. The first is that coal should be used as a substitute for oil and natural gas. The second is that coal should be burned directly where possible, or converted to gas or liquid, rather than used to produce electricity, because electric power generation is wasteful. The third is that solar energy and other renewable sources should be developed commercialized as rapidly as possible.

It follows that, from the point of view of the NEP, electricity is not a desirable substitute for oil or natural gas. Its use should grow as slowly as possible, and should be limited to those areas where coal, oil or gas cannot be used. Expanded electricity would consume coal wastefully, stimulate unwanted nuclear power, and sometimes use oil or natural gas; it is a form of energy, to be conserved and not promoted; and it represents powerful competition to solar energy, which must be developed for the long term.

EFFECTS ON WASTE HEAT UTILIZATION

The result of these generally negative views of electricity is a lack of government interest in waste heat utilization. The major thrust of Federal energy policy lies in other directions, and efforts to improve the efficiency of electric power generation, while meritorious, are clearly not central to the model. The major applications of waste heat—district heating from electric power generating stations, for example—do not appear, in this view, worth the cost and effort to overcome the obstacles impeding them.

ALTERNATIVE VIEWS OF THE NATIONAL ENERGY PICTURE

It is obvious that the Congress has not fully accepted the energy model contained in the National Energy Plan. Although some parts of the plan were finally enacted, some major features were not, and the legislation that emerged was much altered from the original proposals.

At first, most opposition to the plan was based on the view that, while the major goal of reducing consumption of oil was generally right, the strategy proposed was defective. More recently, a point of view has developed that even the major premise—the imminent exhaustion of oil and natural gas—is incorrect, and that the draconian measures proposed to reduce consumption of those two fuels are unnecessary and therefore harmful.

In the view of those critics who accept the goal but reject the strategy, the major defect of the NEP is its disregard for the competing interests involved in carrying it out. In addition to reducing consumption of imported oil, an energy policy must alleviate the economic disruptions caused by the changes in the energy picture resulting from the oil embargo and the rise of the oil cartel; and it must deal with these problems in a manner that protects the environment to the greatest extent possible. While the NEP speaks to all of these goals, it fails to acknowledge that they are to a degree contradictory, and that measures to achieve one—raising the price of oil or gas to reduce consumption, for example—may have negative effects on another—such as keeping prices in check. The thrashing around in Congress over the National Energy Act as submitted by the Administration was to a large extent the result of attempts to balance and reconcile these competing interests.

To a lesser extent, opposition to the NEP derived from its view of electric power, and particularly nuclear power, as an undesirable component of the national energy picture. The debate over this question is clearly not over.

The growing challenge to the NEP approach to energy policy, however, lies in the questioning of the importance of reducing consumption of oil by government action. In this view, oil and gas are not running out now; long term supplies are plentiful, at a price, which may be two or three times the present world price of oil. If liquid petroleum is running low—and the rapid increase in estimated resources in Mexico in the past six months casts doubt even on this premise—other resources, such as shale or tar sands, can take its place. The energy challenge, therefore, will be met in the marketplace, in response to higher prices. An indication that this is already taking place is the reduced growth in energy consumption in 1977 and 1978, reflecting a changing ratio between energy and gross national product.

A corollary to this view is that economic growth itself will be substantially affected by the higher prices of energy, leading to further reductions in the growth rate of energy consumption. In this case, the challenge of energy policy will be to maintain economic prosperity in an era when higher productivity of labor cannot be bought by ever-cheaper increments of energy.

SUMMARY AND CONCLUSION

This rather gloomy view of the support that waste heat utilization has received, and the reasons for it, may serve as an aid in determining what measures may be taken to overcome obstacles to receiving further support. Clearly the initiative in demonstrating the value of pursuing this program must come from the industry itself. Workshops such as this one, which lay out the scope of opportunities and obstacles in the various waste heat options, are one method of making such demonstrations. If the results are encouraging, follow-up efforts through industry representatives might be worth considering.

One source of confusion concerning waste heat utilization is the broad variety of projects that can be comprehended under the subject. These range from massive concepts of residential and commercial district heating of the sort practiced in Germany and Denmark—practical technologies that would yield massive savings of energy but would require equally massive changes in energy consumption patterns—to rather modest programs that would be implemented on a decentralized or site-by-site basis.

Another factor making communication difficult in this area is the restriction of the topic to power plant waste heat. Although this is a major source of low-grade heat, there are others which presumably could profit from progress in utilization technology.

DISTRICT HEATING

The confusion becomes critical in the area of district heating for residential or commercial buildings. As other speakers at this workshop have indicated, district heating by hot water from power plant condensers could be technologically feasible, but only if the temperature of the water is augmented by one of a number of methods.

The need for such augmentation seems to take district heating out of "waste heat utilization" into "cogeneration," particularly if the necessary augmentation is derived from the power plant itself, at the expense of operating efficiency in the production of electricity. Never-the less, it would seem obvious that a power plant that produced electricity with 35 percent efficiency but abandoned the other 65 percent to the environment would be operating less efficiently—from an energy standpoint—than the same plant utilizing 60 percent of its heat energy in a combined system of district heating and electric power production, even if its electric output represented only 25 percent or 30 percent of input energy. The economic efficiency of such a system, however, is not at all so certain, and this uncertainty probably explains the skepticism about district heating that is sometimes expressed by utility representatives.

The issue of district heating is relevant to the consideration that has occupied the major portion of this presentation: the significance of the energy policy debate that is going on at present in Washington, and its influence on the future of the electric power industry. Major components of this debate are the perceived inefficiency of electric power production and the competition between solar power and electricity, particularly in residential heating.

It seems clear that the uses of waste heat that are nearest to commercial viability—aquaculture and agricultural uses such as greenhouse heating—would use only a small portion of power plant waste heat, even if fully exploited, although the benefits from such activities appear well worth the effort to develop them. On the other hand, district heating and industrial uses of waste heat, up to and including cogeneration, could use large amounts of power plant condenser heat, thus going far to neutralize the criticisms based on electric power generation inefficiencies.

It is also possible that district heating could have a significant role to play in easing the competition with solar energy. Problems of compatibility between solar heating and electric power have been well documented, particularly the aspect that back-up of solar heating by electricity would tend to aggravate the difference between average and peak electric power demands. District heating by hot water from power plants, on the other hand, could conceivably be integrated with solar heating systems, in such a way that they would be complementary rather than competitive. Particularly if both systems were connected with heat storage systems, such an integration might increase the usability of both sources of low-grade heat so as to make the overall system practical.

The most effective Government role in the development of waste heat utilization appears to vary according to the technologies involved. In aquaculture and agriculture, the demonstration stage has been well advanced, and the needs appear to lie most in the easing of environmental and regulatory obstacles in the way of commercialization of these technologies. However, since many users of waste heat in these areas can be expected to be small firms and enterprises, some form of capital formation aid might be useful.

A Government role in the development of district heating systems, if considered appropriate or advisable, might be significantly larger than it would be in the case of acquaculture and agricultural use of waste heat. Since district heating projects would be large and capital intensive, and would require substantial activity outside the traditional area of electric utility activity, progress might be more rapid with the help of Government-sponsored demonstration programs.

Government participation could also ease some of the myriad financial and regulatory entanglements that a utility would be involved in if it were to venture into such a new and massive enterprise. Since wide use of district heating would further the national goal of reducing consumption of oil and natural gas, the Federal Government may find it appropriate to use its credit and resources to forward the technology.

On the other hand, utilities might view with some misgivings any large new Federal involvement in their already delicate relationships with consumers, State and local regulatory agencies, and the general public. Decisions on a significant DOE role in promoting district heating projects would inevitably be highly controversial.

COGENERATION AND WASTE HEAT–IV

(By J. Karkheck, et. al.)

The next article compares the widespread use of district heating in some Northern European countries with the market for similar technology in the U.S. and finds the prospects encouraging. It includes a cost study of a possible district heating system for the city of Philadelphia.

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PROSPECTS FOR DISTRICT HEATING IN THE UNITED STATES

The oil crisis of 1973 made more visible the limits of the U.S. and world oil and gas resources and the political and economical uncertainties inherent in U.S. dependence on foreign oil. Appreciation of these factors has sparked increased research and development in the United States on new and improved technologies for energy supply. However, the cost and difficulty of achieving dramatic gains in energy supplies has resulted in great interest in methods of energy conservation. Energy can be conserved in a number of ways: by reducing demand, by improving the efficiency of end-use devices, and by multipurpose, that is, total energy, use. For example, oil or gas fuel used for home heating can be conserved by: (i) turning down the thermostat in the house; (ii) improving the combustion efficiency of the furnace and the insulation efficiency of the house; or (iii) multipurpose use which, in many cases, can save large amounts of energy without excessive cost or change in life style. For space and water heating systems, energy is only needed at relatively low temperatures—that is, 50° to 100°C. In many situations waste heat from electrical generation plants or industry could be used to meet residential and commercial space and hot water energy demands with resultant large savings in the oil and gas resources now consumed for such purposes.

Space and water heating together currently account for 19 percent of the total U.S. energy demand. Each year 1 billion barrels of oil and 0.2×10^{12} cubic meters of natural gas are consumed in the United States to meet these demands.

In many parts of the world, residential and commercial space and water heat is supplied through large-scale district heating systems. Such systems typically supply hot water at a temperature of about 100°C from a small number of localized sources through a grid of buried transmission and distribution pipes to many thousands of individual consumers. In this article, district heating refers only to space and water heating applications.

District heating systems have not been implemented to any significant degree in the United States. To some extent this has been a result of custom and institutional barriers, but for the most part has reflected the condition that consumers could generally meet their space heat and hot water needs more cheaply with individual heating systems than with district heating systems. The recent large increases in the cost of fossil fuels has made district heating systems much more attractive, however. This trend will continue and the balance will shift even further toward the more efficient district heating systems as energy supplies become scarcer. In addition, demographic projections show the urbanization trend continuing in the United States, with the emergence of new urban areas as well as intensification of population in existing ones. This will also favor a change to district heating.

In studies on the feasibility of district heating systems in the United States [1] the focus has been, in general, on the implementation and costs of systems for "new towns," where the district heat system would be constructed as part of a large new residential area. Such applications would be very limited, however, because the vast bulk of the U.S. population will continue to live in existing urban and suburban areas. Additional housing construction will occur in these existing areas but it will represent a relatively modest increase over that already in place, and it will be subject to limitations imposed by existing utilities and roads, for example.

Any significant implementation of district heating in the United States would require the installation of transmission and distribution pipes in existing residential and commercial areas. The laying of pipes under existing pavement will involve costs and public inconvenience substantially greater than those characteristic of systems built in new towns.

WORLD STATUS OF DISTRICT HEATING

Two obstacles to the implementation of district heating systems are mobilization of capital and institutional barriers. Such systems are expensive and usually affect many groups with conflicting interests. Probably only through federal participation could the planning and funding of such large projects be carried out. In fact, district heating systems have been implemented to the greatest extent in countries where the government has played a central role in planning and finance.

District heating systems exist in almost all European countries. Though an old idea, large portions of existing systems were installed during the period of rebuilding after World War II. Since then, district heating has taken a strong hold in Northern Europe and has become a matter of policy in Eastern European countries.

Though precise values for the number of consumers served by district heating systems are not available, approximate values can be estimated by analysis of the heating capacities of existing and proposed district heating systems. A rule of thumb is that the per capita consumption for space and water heat is 3 to 4 kilowatts under peak conditions. On this basis, Sweden is currently meeting the heating needs of about 1.5 to 2 million people or 20 to 25 percent of its population, through district heating systems. This includes several large cities such as Västeras and Malmo in which district heating supplies almost the entire population. Based on growth of its nuclear power program the Swedes project further growth of district heating to an additional 1 million people, including the residents of Stockholm, within the next 10 years. Overall goals call for district heat service to all cities, the waste heat sources being electric power plants and refuse incinerators.

In West Germany, about 3 million people, or 6 percent of the population, are now served by district heat systems. However, an extensive 2-year government study, which will soon be completed, assesses the characteristics of a nationwide "super grid" which will involve interconnected service to all cities with populations of 40,000 or more, using waste heat produced by electric generating plants and industrial processes. It is estimated that 94 percent of the space and water heat demand in West Germany can be met through this scheme at a capital investment of $18.[2] Besides the prime motivation of conservation, large-scale use of district heating also helps to minimize the problem of disposing of waste heat. Alternative uses for waste heat include agriculture, and studies in West Germany indicate that 50 km^2 of arable land could be heated sufficiently well by the heat output from a 1200-Mw nuclear electric plant to extend the spring and fall growing seasons. Two such projects are under way at Neurath and Gundremmingen. Thus, there may be a number of competing markets for "waste" heat.

Denmark has service, at present, to 32 percent of its population, highest in Western Europe, using refuse incinerators, electric plants, and oil-fired boilers as heat sources. For the future, Denmark has indicated the desirability of using waste heat from nuclear electric plants, as have France, Switzerland and other countries. Finland currently has extensive district heating systems, reaching a total of 14 percent of all homes in the country. The government plans additional connections for a half-million people in Greater Helsinki alone within the next 10 years, using waste heat from nuclear electric plants.

The Eastern European countries have followed the lead of the Soviet Union in establishing a formal government position on the utilization of heat produced in conjunction with electricity. The Soviet Union is the world leader in implementing district heating with waste heat utilization. Seventy percent of the urban heat demand and 54 percent of the entire space and water heat load is met through district heating. Moscow, Leningrad, Kharkov, Kiev, Minsk, Rostov, and other cities have extensive district heating networks. Sixty percent of the district heat is supplied by heat-electric plants, and about one-third of all electric plants operate in this dual mode. This situation has been expedited by the government position that waste heat produced by large power plants should be utilized.

In all of these countries, district heat has been cost competitive with other heating methods. Two further conclusions can be drawn: almost all of the extant and projected district heating systems use hot water as the heat transport medium, and because of cost, environmental, and energy conservation benefits, Europeans project substantial increases in district heating in conjunction with the development of nuclear power.

INSTITUTIONAL OBSTACLES TO DISTRICT HEATING IN THE UNITED STATES

That district heating is enjoying success in Europe but not in this country is primarily a reflection of custom and institutional obstacles and not technical considerations. It might be argued that district heating has had the greatest success in countries having cold climates and that the U.S. climate is not suited to district heating. The cost of district heat is determined by system cost and total energy demand, which in turn depend on labor and material cost, population density, total population, climate, and the insulation and floor space characteristics of residential and commercial structures. These last quantities can be reduced to per capita consumption values. Table 1 shows that, on the basis of per capita residential space heat consumption, both the power density and the total energy demand for heating in American cities are comparable to those in European cities in which a substantial part of the demand is met with district heating. This is because American homes are not as well insulated as those in Europe, for example, and have greater per capita living space. Omitted from this table is a comparison of commercial space heat demands and water heat consumption. The former probably parallels the residential comparison, but the latter shows that Americans consume roughly twice as much heat in this sector as do Europeans. It follows that many American cities are as suited to district heating on the basis of energy demand as their European counterparts. Since hourly wage reflects to a degree the materials cost as well as labor expense, it is also apparent that many American cities should be as economically suited to district heating as their European counterparts. That district heating cannot be applied everywhere in this country, because of the pronounced variations in climate, should not diminish its appeal.

TABLE 1.—A COMPARISON BETWEEN SEVERAL EUROPEAN CITIES KNOWN TO HAVE EXTENSIVE DISTRICT HEATING SYSTEMS AND SIMILAR AMERICAN CITIES

City	Climate[1]	Total population (thousands)	Population density (people per square kilometer)	Annual per capita residential space heat consumption (Gj)	Hourly wage (U.S. dollars)[2]
Stockholm	8, 100	750	4, 015	23	7. 12
Malmo	6, 700	254	2, 340	19	
Helsinki[3]	8, 400	750	600	18	[4] NA
Hamburg	6, 300	1, 800	2, 390	21	6. 19
West Berlin	6, 100	2, 000	4, 170	20	
Denver	6, 300	515	2, 080	34	------------
Chicago	6, 200	3, 367	5, 840	33	6. 22
Minneapolis	8, 400	434	3, 040	45	
Detroit	6, 200	1, 511	4, 230	33	
Buffalo	7, 100	463	4, 330	38	
New York	5, 000	7, 895	10, 200	27	------------

[1] Calculated as degree-days: cumulative average daily variation below 65° F (18° C).
[2] 1975 national hourly wages, including benefits.
[3] Helsinki metropolitan area.
[4] Not applicable.

Another condition that influences the viability of district heating is availability and cost of alternative energy sources. But, even though oil was plentiful and cheap, worldwide, until a few years ago, district heating still became popular in Europe and not in the United States. Most of the early systems received heat from thermal plants which employed large fossil-fueled furnaces that were considerably more energy efficient and less air polluting than individual home furnaces. Appreciation of these factors helped to provide incentive for the European pioneering efforts in district heating. The following nontechnical considerations demonstrate the primary obstacles for district heating technology in the United States.

One factor contributing to the lack of interest in district heating systems in the United States has been the use of steam as the heat transport medium in U.S. systems. Steam is well suited to the transport of heat over short distances and can effectively meet the high-density demand encountered in the central core of cities. However, steam is inherently difficult and costly to transmit over long distances. Thus, there has been little incentive for a steam utility to grow with its city. This early experience with district heating established the pattern by which district heating is still viewed today in the United States, where steam supply systems still serve small core areas of cities at a level equivalent to a total population of about 2.5 million [*3*]. The European experience has clearly demonstrated that hot water transport is more economical and permits the use of larger systems serving greater populations.

Finally, in the United States, space and water heating systems have generally been in the realm of private enterprise. However, district heating systems are very capital intensive, and though profit margin is there, the primary benefits of such systems would be conservation of scarce energy resources and reduction in balance of payments, and these benefits would be readily perceived only at a national policy level. Thus government involvement appears mandatory for the promotion of district heating, not only for funding but also because it can include national considerations in the decision process. At the same time, government involvement raises complex problems regarding conflict of interest. Financing and administration of heating systems could be handled in like manner to cold water and sewage systems. The fact that the commodity provided by district heating systems has hitherto been supplied by private enterprise means that government operation of district heating systems would put the government in competition with private enterprise. However, there have been similar difficulties abroad that were surmounted without compromising either national or private interests. In view of the substantial national benefits of district heating, it is not unreasonable to expect that similar resolution could be achieved in the United States.

Cost and Implementation Projections

We have examined the potential costs of installing district heating systems in nine urban regions in the United States, and have sought to define the feasibility and economic limits of district heating systems on a national level [*4*].

The nine regions were selected to cover a representative range of existing U.S. population densities, housing profiles, and climates. We analyzed each region demographically, using Census Tract data. Population density was mapped for each region and the most densely populated tracts were aggregated to form large contiguous areas that were judged to be most economically served by district heating (see Figure 1 for an example). The percentages of the populations in our model district heating areas are shown in Table 2. We could have encompassed greater percentages than those shown, thus the analyses do not represent the optimum implementation level but rather are conservative in approach.

Table 2.—Cost projections for district heat (DH), at point of consumption for, service levels indicated—Data are for cities, except where indicated; DH, district heating

Urban area	Population encompassed by DH system (percent)	Total population served by DH system (thousands)	Average cost for heat supplied (dollar/Gj)	
			From plants sited within the area served	From plants sited 32 to 40 kilometers away from area served
New York	95	7,500	0.85	1.09
Chicago	33	1,098	.74	1.10
Philadelphia	79	1,543	.76	1.00
Los Angeles	33	933	1.44	1.73
New Orleans	31	185	1.08	1.53
Baton Rouge	45	74	1.78	2.43
Jersey City[1]	83	503	.80	1.08
Newark[2]	64	481	.79	1.08
Paterson[2]	50	173	.90	1.26

[1] Data for standard metropolitan statistical area (SMSA).

[2] Data for part of SMSA.

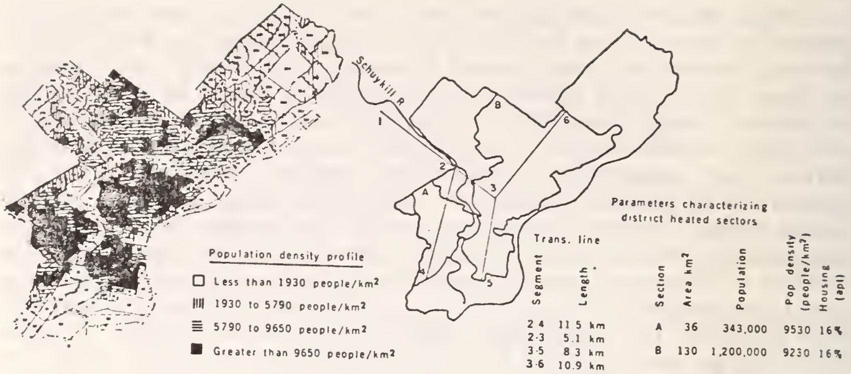

Schuylkill R
1
2
3
4
5
6
A
B
Population density profile
☐ Less than 1930 people/km²
▥ 1930 to 5790 people/km²
≣ 5790 to 9650 people/km²
■ Greater than 9650 people/km²
Parameters characterizing district heated sectors
Trans. line
Segment Length
2 4 11 5 km
2·3 5.1 km
3·5 8 3 km
3·6 10.9 km
Section Area km² Population Pop density (people/km²) Housing (apt)
A 36 343,000 9530 16%
B 130 1,200,000 9230 16%

FIGURE 1.—The left figure shows the profile of population density for Philadelphia, as obtained from an analysis of Census Tract data. Individual contiguous tracts were collected together to form the large heavily populated sections shown in the right figure. Model district heating systems were constructed on the basis of the gross demographic parameters shown. The transmission network shown was designed for a single-site heat source such as the proposed nuclear power complex at Limerick.

Heating needs for each area were computed on the basis of national average per capita residential and commercial floor space allotments, net regional unit heat demands, and local degree-day data (see Table 1). Model district heating systems were constructed for each region; urethane-insulated pipes constructed of polymer concrete and lined with polymer [5] were buried to the specifications of the cold water industry. Both supply and return pipes were buried in the same trench. Estimates of pipe installation costs were based on current costs of installing cold water mains locally, as reported by the various water authorities. These were adjusted to accommodate the insulation cost and greater dimensions of hot water pipes. Finally, the unit heat costs shown in Table 2, which do not include any charge for the waste heat itself, were computed by assuming yearly fixed charges of 10 percent of the capital investment, plus a charge for pumping energy. These costs were apportioned over the projected annual heat demand of the population served. Waste heat costs are discussed in the next section.

Comparison of the last two columns in Table 2 shows that transmission over the distances typical of the separation between fission power plants and large population centers (32 to 40 km) is not a prohibitive cost effect. A brief summary of the details of the Philadelphia district heating system design is given in Table 3. In particular, pumping power is that needed to overcome frictional losses in the transmission and distribution system. Conduction loss reflects the temperature drop of hot water consumed at the extreme end of the system. Overall temperature drop includes supply and return conduction losses and a useful drop of about 42° C in each consumer building. Service connections to houses, apartments, and commercial buildings should be somewhat cheaper than fossil burners sized for these structures. In Philadelphia, the cost of connecting a house to the system was estimated to be $14 per meter of length, and apartment or commercial connections to be $48.25 per meter. Fifteen meters was a typical length requirement. In summary, the regional analyses indicate a favorable economic picture for district heating in American cities, and show that portions of some cities with mild winters could be served by district heating systems.

The second stage of our study was concerned with projections of national levels of implementation of district heating within the economic limits commensurate with alternative energy sources and the accompanying conservation of fossil fuels. For this task we used average values for degree-day data, and installation costs which were computed on the basis of a sample of all cities with populations of 100,000 or more. This sample constituted a total population of 51 million (1970 Census) and yielded a good approximation to national averages. Average heat demand and system capital cost were then computed as a function of density of the population served by a given system. Addition of pumping energy costs and amortization of the capital cost then yielded the profile of unit heat charge (not including waste heat cost) as dependent on population density shown in Figure 2. We projected levels of implementation by coupling this profile to the population density studies of Haaland and Heath [6]. Total population levels that were serviceable at heat costs less than or equal to the effective energy costs [7] of natural gas, imported oil, and electricity appear as points 1, 2, 3 on curve A in Figure 3. In addition, curve A shows the projected average cost of heat at each level of population served. Since virtually all citizens bear the cost of imported oil to some extent, district heating could probably be implemented at that level with all customers being charged a uniform price. This would permit district heating service to more than half the population (point 4, curve A).

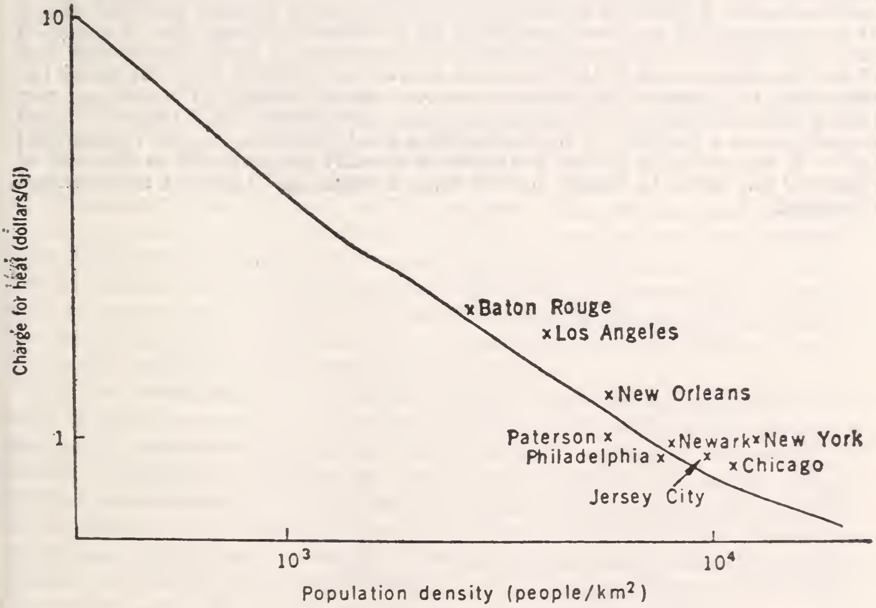
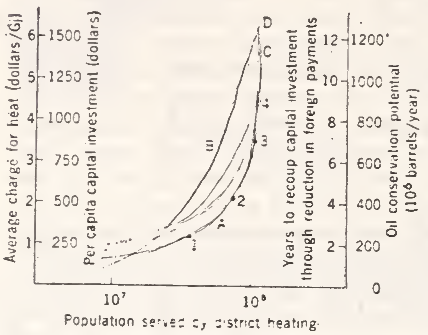


Figure 2. A curve showing the projected average unit heat cost as a function of gross population density within the area served by each district heating system. Projections are based on nationally averaged per capita space and water heat demand, average labor costs, and 10 percent amortization of capital. Shown for comparison (*X*'s) are the cost projections obtained in our detailed regional analyses. Rural transmission cost and price of waste heat at the source are omitted, but pumping energy cost is included.



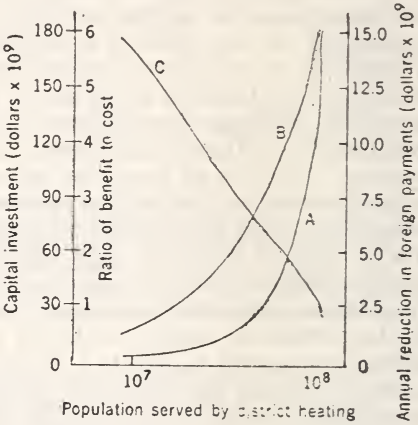


Figure 3 (left). Curve A shows the projected average cost of heat as a function of total population served by district heating. The sharp rise at about 100,000,000 is due to the disproportionate system expense at low population densities. The points show: 1, population serviceable (38 million) at an average charge of $1.18 and maximum of $2 which is the effective energy cost of natural gas: 2.73 million at an average of $2 and maximum of $4.25, the effective energy cost of imported oil: 3, 102 million at an average of $3.50 and maximum of $8.50, the average cost of electric energy: and 4, 110 million at an average of $4.25. Curve B shows the equivalent oil conservation potential, curve C shows the capital investment pay back period, and curve D shows the per capita investment. Fig. 4 (right). Capital projections as a function of implementation level. Curve A, capital investment; curve B, reduction in foreign payments is directly proportional to the cost of imported oil; curve C, benefit to cost ratio is based on 10 percent amortization of capital.

TABLE 3.—*Summary of characteristics of the district heating system design for Philadelphia.*

Item	*Value*
1. Population served (thousands)	1, 543
2. Average density (people/km^2)	9, 270
3. Annual heat load (10^{15} joules)	62. 4
4. Rural transmission line [1]:	
Inside diameter (m)	2. 8
Unit cost (dollar/km × 10^6)	2. 9
Length (km) and site (Limerick)	35
5. City transmission system [1]:	
Segment (see figure 1)	2 to 4
Inside diameter (m)	1. 5
Unit cost (dollar/km × 10^6)	1. 8
Length (km)	11. 5
Segment	2 to 3
Inside diameter (m)	2. 5
Unit cost (dollar/km × 10^6)	4. 25
Length (km)	5. 1
Segment	3 to 5
Inside diameter (m)	1. 6
Unit cost (dollar/km × 10^6)	2
Length (km)	8. 3
Segment	3 to 6
Inside diameter (m)	2. 2
Unit cost (dollar/km × 10^6)	3. 25
Length (km)	10. 9
6. Distribution system [2]:	
Inside diameter (m)	0. 46
Unit cost (dollar/km × 10^6)	0. 32
Length (km)	120
Inside diameter (m)	0. 41
Unit cost (dollar/km × 10^6)	0. 28
Length (km)	99
Inside diameter (m)	0. 25
Unit cost (dollar/km × 10^6)	0. 153
Length (km)	2. 015
7. Total system cost (items) 4 plus 5 plus 6), (dollars × 10^6)	574
8. Pumping power (percentage of power supplied)	1. 1
9. Conduction loss:	
Power flow percent	3. 7
Temperature drop (°C)	1. 8
10. Overall temperature drop (°C)	47

[1] Allowing for a pressure drop of 1.7×10^4 newton m^{-2} km^{-1}.

[2] Allowing for a pressure drop of 6.4×10^3 newton m^{-2} km^{-1}.

Utilization of waste heat in this manner saves substantial amounts of oil, natural gas, and electricity. The oil equivalent conservation potential (curve B, Figure 3) is roughly a linear function of population served. This is a direct consequence of the use of population density as the independent variable (Figure 2). Geographical differentiation, for example, is not evident at this level of description. Consequently, this curve exhibits only average projections.

Capital investment in district heating systems as a function of total population served is summarized in Figure 4. Also shown is the yearly reduction in balance of payments at current imported oil prices. Though an increase in the cost of foreign oil could permit further penetration of district heating up to the new economic bounds, the benefit to cost ratio (Figure 4) shows that this effect would be marginal. The primary benefit afforded by district heating in this context would be stability of energy cost. The significance of this for the nation and the consumer cannot be overemphasized.

In summary, we find that between 50 and 55 percent of the U.S. population could be served by district heating at the current economic levels dictated by foreign oil prices. Total investment in district heating systems is estimated at $180 billion; the resultant oil conservation of 1.1×10^9 barrels per year (currently about 55 percent of imports) would translate into a reduction in foreign payments of $13 billion per year. In terms of national benefit, the district heating scheme would pay for itself after 14 full years of operation at maximum implementation or sooner if imported crude oil were to increase in price. The capital investment corresponds to an average of $5,000 per household connected, for a service that can satisfy the entire heat demand of each consumer.

AVAILABILITY OF WASTE HEAT

For conventional steam-electric plants fired by fossil fuels the average efficiency of conversion of fuel energy to electricity is 33 percent. Fifty-two percent of the fuel energy is discarded through the condenser as waste heat and 15 percent is lost up the stack or within the plant. In existing light water reactor (LWR) nuclear power plants the waste heat is about 62 percent of the input energy, thermal plant losses amount to 5 percent, and electricity is produced at the same efficiency. The annual production of waste heat from existing steam-electric plants is about 8.4×10^{18} joules, an amount greater than the total amount of energy consumed for space and water heating per year in the United States (that is, net consumption, not including conversion losses).

The waste heat from the steam condenser corresponds to the saturation temperature of steam at an absolute pressure of about 0.05 atmosphere, which is normally the outlet pressure from the steam turbine. The waste heat temperature is thus about 40°C and is too low to be used in district heating systems. However, if the outlet steam pressure to the condenser is increased to 1 atm, the steam condenses at 100°C which is sufficiently hot for practical district heat systems. The principal effect of the higher condenser temperature is a reduction in thermal efficiency, that is, in conversion of thermal input to electricity. For each unit of waste heat produced at 100°C, about 0.1 of a unit of electricity is lost, which reduces the conversion efficiency from 33 to about 25 percent. From a total energy standpoint, however, the dual production of electricity and hot water for space heat is much more efficient. For example, the production of 100 units of electricity and 240 units of space heat by sepatate single-purpose fossil plants requires an input of 300 and 340 units of fuel, respectively, for conversion efficiencies of 33 and 70 percent. The overall average efficiency is then 53 percent to satisfy both demands. A fossil fuel electric plant which operates at the higher condenser temperature, with waste heat being used in a district heating system, will produce the same 100 units of electric and 240 units of usable heat with a fuel input of 400 units, yielding an overall energy conversion efficiency of 85 percent and a fuel savings of 240 units. Nuclear power plants operating in the dual mode offer higher efficiency (95 percent) and greater fuel savings because of the lack of stack gas losses.

Table 4 illustrates the effect of district heating on annual U.S. fuel consumption for three reference years [8]. The district heat load was assumed to be distributed among steam-electric plants by fuel type in proportion to the projected installed capacities. Large reductions in annual oil and gas consumption and overall energy consumption would be achieved if district heat systems were used at the indicated levels. Increases in total population might open new markets for district heating and allow extension of established systems into suburban areas, thus increasing the oil and gas savings. As new construction with better insulation characteristics becomes significant [in about the year 2000[8]], the net energy savings levels off. At the same time, economic conditions may favor implementation of district heating to levels beyond those assumed in Table 4.

The gas that would be conserved could be redirected into applications that would further decrease oil consumption. In all cases the equivalent oil savings would exceed the amount of oil that would be consumed by the space and water heating sectors if district heating were not implemented. Thus, use of district heating could eliminate the use of oil in the space and water heating sectors.

Additional generating capacity would not be necessary in order to maintain electric output at demand levels. The current average steam-electric plant factor of 53 percent [9] shows that on the average almost half of all steam-electric capacity is not in use throughout the year. Two factors contribute to this disuse: plant maintenance and temporal variations in demand. The amount of disuse contributed by the latter factor varies with each utility, but total additional capacity needs can still be projected without consideration of the details of operation of each utility.

TABLE 4.—ANNUAL FUEL AND ENERGY SAVINGS PROJECTED ON THE BASIS OF DISTRICT HEATING SERVICE TO HALF THE CURRENT U.S. POPULATION AND, FOR ILLUSTRATION, TO HALF THE PROJECTED POPULATIONS, FOR 3 REFERENCE YEARS, BASED ON THE ASSUMPTION THAT WASTE HEAT FROM POWERPLANTS WILL BE UTILIZED

Population served (millions)	District heat demand (10^{18} joules)	Steam-electric generation fuel mix (percent)				Extra fuel required by powerplants in dual mode operation/(10^{18} joules)				Annual savings for U.S. energy system *			
		Oil	Coal	Gas	Nuclear	Oil	Coal	Gas	Nuclear	Net (10^{18} joules)	Oil (10^{18} joules)	Gas (10^{18} joules)	Oil equivalent (10^9 barrels)
Reference year, 1972:													
103	3.8	18.8	51.5	25.9	3.8	0.3	0.81	0.41	0.05	5.0	2.6	3.3	1.1
Reference year, 1985:													
103	3.8	8.3	44	9.4	38.3	.14	.69	.15	.52	5.1	2.7	3.6	1.2
115	4.4	8.3	44	9.4	38.3	.15	.8	.17	.6	5.5	3.2	3.8	1.3
Reference year, 2000:													
103	3.8	3.3	30	3.2	63.5	.05	.47	.05	.86	5.2	2.8	3.7	1.2
115	5.4	3.3	30	3.2	63.5	.07	.67	.07	1.21	5.3	3.5	3.7	1.32

*District heat plus electric production.

Upper limits for plant factors are 75 to 80 percent and are readily attained within the electric industry. These should reflect maintenance time requirements and suggest that, on the average, roughly one-quarter of all generating capacity is used intermittently throughout the year. District heating to half of the population using electric plant waste heat would require operation of one-third more generating capacity by those utilities serving the district heated regions. If one assumes that electricity would not be imported by the heat-electric utilities and that half of the intermittently used capacity could be fully mobilized, then the net additional capacity needed would be 4 percent of the current total steam-electric capacity. This requirement would be easily accommodated by the new steam-electric capacity projected to come online within the next decade and which amounts to almost a 100 percent increase in installed capacity.

The amount of extra fuel that would be used by electric utilities that also supply heat is shown in Table 4. One hundred additional units of fossil fuel are required to produce 240 units of usable heat, and for LWR plants the ratio is 1:2.8. The cost of additional fuel may be recouped by charging for waste heat in these proportions. Waste heat would cost 14 cents per gigajoule for uranium fuel, 21 cents for natural gas, 32 cents for coal, and 95 cents for imported oil [*10*].

Other waste heat sources exist, though not in the same quantity nor at the same uniform distribution as electric plants. Certain industries, such as steel, produce waste heat that could be used for district heating systems. Some industries now discard heat at temperatures too low to be useful in district heating systems. However, this is often because of equipment design, not thermodynamic necessity, and the temperature could be raised by procedural or equipment modifications without affecting the process efficiency. Finally, refuse incineration could be a source of waste heat as well as a solution to urban waste problems. The garbage produced within a city of average U.S. climate could supply enough heat to meet the full needs of about 7 percent of the city's population. These alternative sources could be used to meet peak demands as well as contribute to the baseload heat supply.

COMPARISON WITH OTHER TECHNOLOGIES

Clearly, district heating is not the only technology option that could significantly reduce oil imports, fossil fuel consumption, and environmental pollution; for example, coal gasification could in principle produce enough synthetic fuel to eliminate oil imports. However, this technology appears to be at least as capital intensive as the district heating scheme with equipment lifetimes (30 years) estimated at half that of the district heating network (at least 60 years). In addition, the cost of synthetic fuels will be strongly affected by the cost of coal, which could rise dramatically in the next few decades. In contrast, waste heat costs are a small part of total district heating costs and should remain so. Once the capital investment in a district heating system is made, the unit charges should remain essentially constant with time. Approximately 80 percent of our present energy end-use devices rely on oil and gas input, so the development of replacement fuels may appear more desirable in the short term than substituting new devices involving less familiar technologies. However, in the long run, new technologies may be more desirable. District heating would appear to be more desirable than coal gasification in the long run, not only because of the necessity to conserve coal resources and reduce environmental pollution, but also because district heating systems should require much less maintenance and repair than equivalent coal gasification plants and fossil fired home heating units.

Solar energy is a more versatile resource than waste heat and in the very long term may be the most important source in the U.S. energy economy, but the nature of its role is not yet defined. With regard to the application to space and water heating, in general, solar heating will not replace conventional heating systems but rather will supplement them. In contrast, district heating systems can replace conventional heating systems, and offer the potential of both larger savings in fossil energy resources, and lower costs, since dual heating systems are not required.

A third method for space and water heating would require either the direct use of electricity generated in nuclear power plants, or the electrolytic generation of hydrogen during off peak periods [*11*] for use as fuel in individual heating systems. These methods would exacerbate the waste heat problem, and go counter to the principle of total energy use.

A comparison between the four options in terms of capital investment (current dollars) for a given power capacity appears in Figure 5. The values shown for the electric plant option are for 1000-Mw baseload plants with a 30-year lifetime. Here, in fact, the district heating option should be substantially more attractive than Figure 5 indicates, because its operating lifetime should be considerably longer than the assumed 50-year amortization period. Consequently, the district heating scheme should have a substantial advantage over more conventional options which would require more frequent replacement and would probably incur large escalations in capital cost when replaced. Energy cost to the consumer is least sensitive to basic fuel cost in the district heating option. Figure 6 shows that district heat supply to up to 50 percent of the population could provide significant savings. In addition, a rise in the cost of fuel would pass on to the consumer in all cases. The relative scale factors relating the proportional increases in fuel charge for the three hearing options are 3 for electricity customers, 1.3 to 1.6 for synthetic fuel customers, and 0.35 to 0.40 for district heat customers.

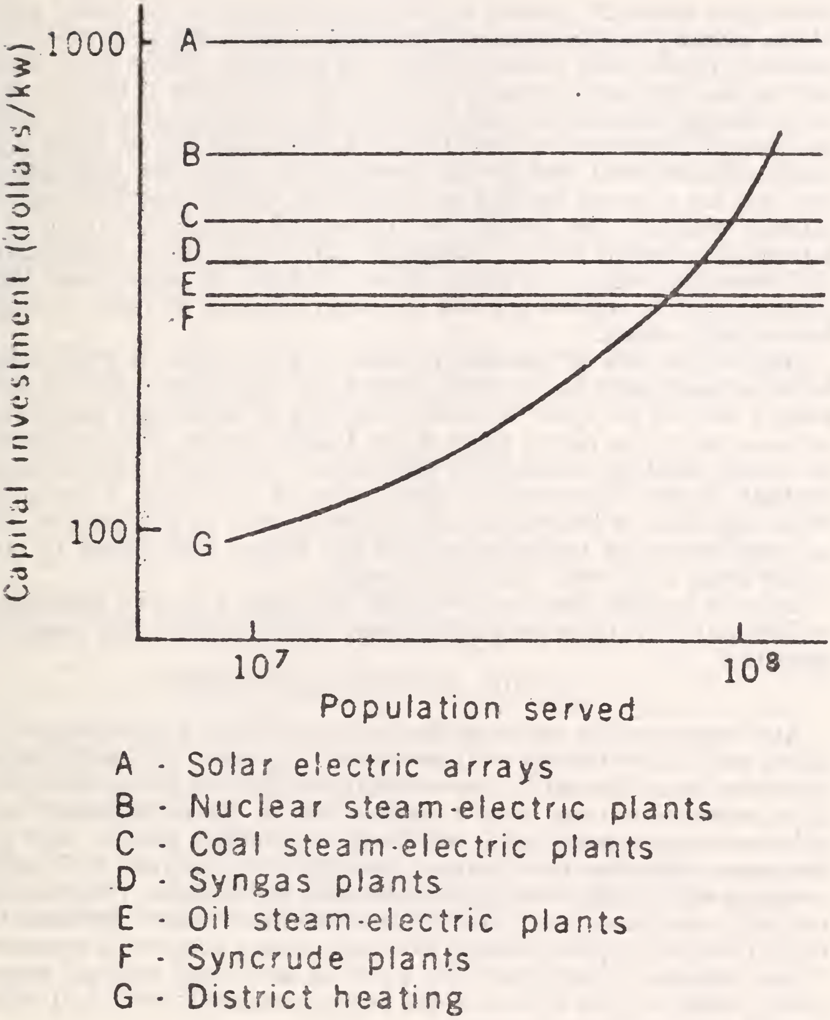


Figure 5. Comparison of capital investment for several technologies. Plant costs and solar array estimate obtained from [8].

Economically, district heating would be superior to solar heating for a large segment of the population. From Fig. 3. curve D, capital investment per household in district heating networks with maximal implementation levels will be about $5000 (costs would be lower with smaller implementation levels). The consumer would probably not pay this directly, but instead would pay a service charge which would amortize the cost of the district heating system. He might pay a connection charge of several hundred dollars, however, which would cover the cost of installation of pipe from the street main to his house. For about the same capital expenditure, a house could be outfitted with solar collectors and thermal storage devices that would meet from about 20 percent of the heating needs in the colder parts of the country up to about 100 percent in the warmest parts of the country. In the solar heating option the consumer might have to lay out capital for both the solar and backup conventional heating systems, though subsidization might be possible, and the consumer might still remain dependent on fossil fuels to a significant degree. There is no single effective heat cost for the combined system since geographical location has a strong bearing on energy mix. At average climate conditions, with half the demand met by solar heat, solar energy cost is estimated at about $14 per gigajoule [12]. While this is competitive with electrical energy in some regions, it must be emphasized that conventional structures are not as energy efficient as those certified for electric heating.

Despite the lack of precision of solar cost estimates, it would seem better economically to invest in district heating systems than in solar energy devices for space and water heating in urban and dense suburban areas in the colder parts of the United States. The installation of district heating networks in these areas would also yield a larger cutback in fuel consumption than curve B in Figure 3 indicates. Solar and district heating should not be viewed as competitors, but as complementary technologies with the former best suited to nonurban areas with relatively mild climates.

District heating has the advantage of being a proved technology in Europe. It requires simple hardware, and is reliable and simple to operate.

DISTRICT HEATING POLICY ISSUES

Any enterprise for reducing the amount of fossil fuel consumed by space and water heating will encounter economic and institutional obstacles, as evidenced by the attempts to improve house insulation. The government must play a central role in the development of a coherent energy program. It will have to establish policies that will overcome obstacles in a manner acceptable to private and public interests while implementing desirable new technologies. Congress has officially recognized this duty in its attempts to allow personal tax deductions for implementation of certain energy conserving measures. These gestures do not constitute a part of an overall national energy policy, however, but indicate some ways government could help effect change in the national interest.

We have shown district heating to be an economically feasible technology for the United States, but its success cannot be guaranteed unless several definitive policy decisions are made. The first is recognition that a particular energy problem might, for technical or economic reasons, optimally have several distinct solutions each of which would best serve a distinct segment of the population. Only with this attitude would the United States be likely to recognize district heating. To provide the greatest benefit to the nation, district heating must be implemented extensively to high levels of population. In many cases, several contiguous cities might be encompassed by a single district heating system being managed by a regional authority. Federal policy would have to provide for several such regional authorities to plan on a local level and solve local problems. That almost all consumers within an area served by district heat use the system is vital. District heating might encounter consumer resistance to change; however, the economics of district heating is attractive in itself and a suitable tax policy could further reward those who use district heat and discourage consumers from using conventional sources. Provision would have to be made for financing the district heating networks and users' equipment where retrofit might be necessary. Long-term government loans could certainly be provided on the basis of it being more beneficial to invest the money internally.

A tax structure that encouraged full use of the energy content of high-grade fuels could make it even more rewarding for an electric utility to use its waste heat in a district heating application. District heating over a large part of any city would certainly eliminate many local home heating fuel businesses, but pipe network construction would produce a net increase in total employment, and operation and maintenance of district heating systems would create new skilled positions. Job dislocation could be minimized by properly scheduling the district heat load buildup.

Finally, federal policy should promulgate the advancement of district heating technology. Since labor would be the dominant cost (about 75 percent in our study) serious consideration should be given to the development of new construction techniques and equipment, such as mechanical moles, that could reduce the labor involved in pipe installation. Pipeline technology could be improved beyond our design. Plastic pipe is undergoing intensive study in Sweden. Extreme durability and the possibility of installation in very long segments might reduce maintenance, replacement, and initial installation costs of plastic pipes to a competitive level. Further development is needed in the technology of plastics to increase their pressure capacity. A composite of materials including plastic inner liner and high-pressure outer jacket such as found on fire hoses might be particularly useful for transmission lines. Reductions in weight and outside diameter decreases all materials and excavation requirements. thus overall costs. Reduction in transmission line costs produces a most pronounced effect in the economics of district heating for isolated cities of low total population (about 25,000 to 100,000).

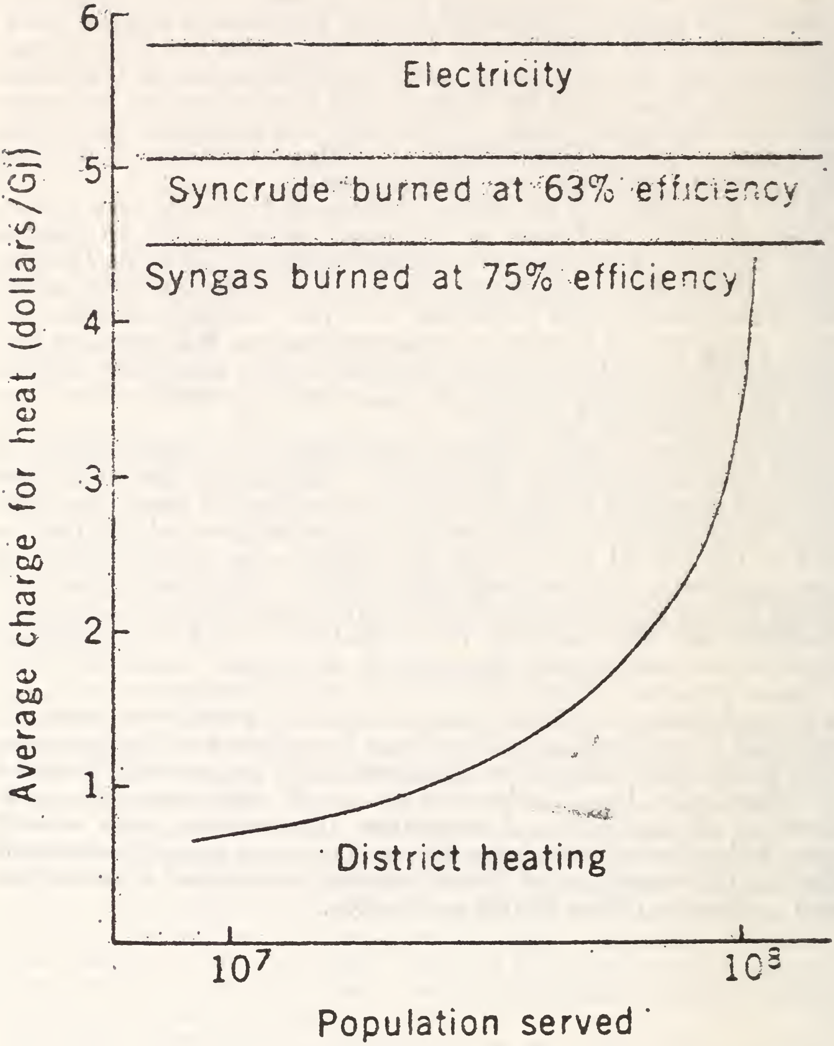


Figure 6. Comparison of net (after conversion) heat costs (fuel only, excludes capital for enduse devices). The electricity curve reflects current electricity prices adjusted for the higher thermal efficiencies of buildings certified for electric heat.

CONCLUSIONS

District heating is a viable technology in many European countries. Many American cities exhibit characteristics similar to those in Europe where district heating now serves a significant portion of the populace and will expand to virtually the entire populace in the near future. In view of the limitations of U.S. oil and gas resources and our increasing dependence on imports, it is necessary for the

United States to take definite steps to reduce consumption, and the implementation of district heating would constitute a sizable step in this direction.

The durability of modern materials ensures that district heating would result in very stable heat costs. This is an important feature which must be emphasized in developing consumer confidence in the scheme. To realize the full potential for national benefit, district heating must be implemented on a national scale through a concerted national program. This will require the involvement of federal agencies in managing finances, producing comprehensive analyses of supply and demand, providing systematic plans and goals for implementing district heating in each urban area, and in furnishing policy measures necessary to ensure acceptance of district heating by the various interest groups. The role which the electric utilities may play in the enactment of such a program should be significant inasmuch as they are a potential source of usable waste heat and have considerable experience in providing reliable utility service.

Though we can undoubtedly borrow heavily from European experience, it is mandatory that several pilot systems be introduced whereby the United States may gain operational experience and develop a procedure for the buildup of very large systems.

District heating is not a universal solution for the space and water heat demand sectors. High costs will prohibit district heating systems from rural and some low-density, warm climate, urban, and suburban areas. Therefore, a complementary technology, such as solar heating, which is suited to these conditions should be developed to reduce fuel consumption within such areas. The point is clear that district heating can and must be seriously considered as an important element in the solutions to our problems of energy supply and demand.

SUMMARY

Large-scale district heating, using waste heat rejected by electric power plants and other sources, is presented as a means of reducing significantly the amount of fossil fuel consumed for residential and commercial space and water heating in the United States. Analysis of the technical and economic aspects of model district heating systems for nine U.S. urban areas shows that district heat service to residential and commercial consumers would be economically attractive. Projections of national service levels show that up to half of the U.S. population could be served by district heating at costs that are competitive with the present costs of imported oil and also with projected costs of new energy forms. An advantage of district heat over the latter is that it is a proved, simple technology.

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COGENERATION AND WASTE HEAT—V

(BY B. C. Kim, et, al.)

The next selection reviews the possible industrial and residential uses of waste heat from power plants and concludes that these uses would generally include some form of augmentation.

The study, which was presented at the Atlanta Waste Heat Workshop in November, discusses various options for increasing the temperature of the waste heat from power plant condensers. One of the more intriguing possibilities mentioned was the use of solar heat in a combined system.

INDUSTRIAL AND RESIDENTIAL USES OF POWERPLANT WASTE HEAT

(By B. C. Kim, W. H. Wilkinson, H. S. Rosenberg, and J. H. Oxley)

INTRODUCTION

The rising cost of energy as well as environmental regulations with regard to atmospheric and thermal pollution have created an incentive for energy conservation in the United States. One method for conserving energy is to use heat which has been discharged from some conversion mechanism or industrial process. Tremendous quantities of waste heat are produced in the U.S. by power generating plants. The quantity exceeds 11 percent of all energy used annually in the U.S. and may increase in the future. [1,2]

In a steam power plant, part of the heating value of the fuel is transferred to water in a boiler; the steam generated expands against the blades of a turbine. The expanded vapors are condensed in a low-temperature heat exchanger and the condensate is pumped back to the boiler for reuse. From the basic principles of thermodynamics, the maximum thermal efficiency attainable by a cyclical process of this type is related to the absolute temperatures for rejection and adding heat.

About 50 percent of the total energy input to a coal-fired electric generating plant is lost to the condenser cooling water as waste heat and 10 percent is lost from the stack. The remaining 40 percent of the heat input is converted to electricity. In nuclear power plants, about 65 percent of the energy input is discharged in the condenser cooling water and 35 percent is converted to electricity.

The temperature of the water and the quantity discharged vary with design and site characteristics. A once-through system with a low-temperature rise condenser (ΔT of about 14° F) requires about 600 gpm of cooling water per MW of generating capacity. [3] For a once-through, high-temperature rise condenser (ΔT of about 28° F), the cooling water requirement is about 350 gpm/MW. In much of the U.S., the condenser discharge temperatures range from 50° F in the winter to 100° F in the summer for a low-temperature rise system. The corresponding discharge temperatures for a high-temperature rise condenser are 64° F in the winter and 115° F in the summer.

Although there are strong incentives for utilizing the heat content of the condenser discharge water, there are several problems associated with its use. These include the relatively low discharge temperature, high utilization costs, the necessity of locating the user near the heat source, the potential interruptable nature of the service, the possibility of chemical contamination, and seasonal variations in source temperature that could be adverse to heat needs.

This paper is a survey of potential industrial and residential uses of the low-grade energy contained in the condenser cooling water discharged from power plants, including a consideration of augmentation methods to enhance the prospects for waste heat utilization.

BACKGROUND

With the exception of in-plant use for boiler feedwater heating, space heating has been the primary outlet for waste heat, and Europe has tended to make more widespread use of this technology than the U.S. This has been caused by the fact that the costs of energy have been higher in Europe than in the U.S., and the average European climate is somewhat colder than that of the U.S. Hot water is the primary heating medium at temperatures slightly under 200° F, but a few systems use steam. Sweden is apparently the only country in the world which has used reject heat from a nuclear electric power station for district heating for civilian purposes for substantial periods of time, but plans are under way for more widespread use of nuclear heat in the future throughout the world. Other applications for waste heat have developed, but generally these applications involve steam at temperatures and pressures considerably higher than what utilities consider to be suitable to release as "waste heat".

Sale of energy for district heating purposes in the United States is more widespread than generally recognized, but at the same time, much of this energy is delivered by steam from old electric plants which no longer produce electricity. At the top of the list of suppliers is Consolidated Edison, which provides about 40 percent of the total merchant steam sold for district heating in this country. However, some four dozen other utilities regularly report on their sales to the International District Heating Association, [4, 5] a trade organization of merchant steam producers. Approximately 15,000 customers in the U.S. are served by this network.[4]

INDUSTRIAL USES

Assessment Criteria

The following factors were considered in assessing the potential application of power plant waste heat to industrial processes:

(1) Process temperature;
(2) Type of process media;
(3) Quantity of usage; and
(4) Percentage of the process heat usage at applicable temperature level relative to the total process heat usage.

Process temperature is probably one of the most important factors that influences waste heat application. In this study, the maximum process temperature was set at 180°F, which would correspond to a heat source temperature of at least 200°F based on a 20°F temperature difference at the hot end of a heat exchanger between the heat source the process medium.

Process media could be broadly divided into two types: liquid and gas. The liquid media, such as water, would be more likely candidate than the gaseous media, such as air, for application of power plant waste heat. The temperature of the heat source is in general much lower for the liquid media than for the gaseous media for economical heat exchanger design.

Economic application of power plant waste heat will depend on the usage; greater usage being favored in general by economy of scale. However, the optimum usage level is not known at this time. If the usage of low-temperature heat constitutes a small fraction of the total process heat requirement, a greater likelihood exists for in-plant recovery and utilization of waste heat that would compete with importation of power plant waste heat. This is evident particularly in some of the largest industrial users of process heat such as petroleum refining, chemicals, pulp and paper, and primary metals.

Potential Applications

There are 45 industries in the four-digit SIC classifications with a total energy usage of 574×10^{12} Btu/yr at a process temperature below 180°F, in the United States in 1974 (refer to Table I). This energy usage represents about 20 percent of the total energy requirement for the 45 industries and is equivalent to the waste heat rejected by about 13,000 MW of electrical generating capacity. If the process temperature criterion is lowered to less then 140°F, the number of industries decreases to 21 and the total energy usage decreases to 136×10^{12} Btu/yr. Similarly, for a process temperature of less than 100°F, there are 6 industries with a total energy usage of 26×10^{12} Btu/yr.[6]

The major users of process heat at temperatures below 180°F are the food processing industry, the textile industry, the furniture industry, the pulp and paper industry, the chemical industry, concrete block manufacturers, iron and steel foundries, and automobile and truck manfacturers. However, not all of these industries are good candidates for the utilization of power plant waste heat.

Food processing.—The food processing industries with significant usage of process heat at process temperatures less than 180° F include: meat packing plants (SIC 2011), sausages and prepared meats (SIC 2013), poultry dressing plants (SIC 2016), natural and processed cheese (SIC 2022), condensed and evaporated milk (SIC 2023), and fluid milk (SIC 2026). The process heat is for generating hot water used for scalding, product washing, and clean-up operations. Although large quantities of wastewater at temperatures comparable to power plant condenser discharge water are generated, the water is usually contaminated and not suitable for waste heat recovery due to concerns about product contamination and the possibility of compromising product quality control standards and government regulatory standards. This enhances the prospect for application of power plant waste heat.

Textile industry.—The textile industries with significant process heat usage at temperatures less than 180° F include: textile finishing plants (SIC 2261 and 2262) and yarn mills (SIC 2281). In the textile finishing plants, the process heat usage is for heating water for washing and bleaching operations and for heating air for drying and curing operations. In the yarn mills, the process heat usage is for heating water for scouring and washing operations.

Large quantities of waste heat are generated in the textile industry. It is estimated that one billion gallons of water in the 120 to 140° F temperature range are discharged daily by the industry. [7] This water is about 20° F hotter than power plant condenser discharge water. The quantity of heat that could be recovered from the water discharged by the textile industry is estimated at 0.33×10^{12} Btu/day with a temperature drop of 40° F, for example from 140° F to 100° F. Based on 300 days/yr operation, the heat recovery could reach 100×10^{12} Btu/yr, which is about twice the process heat usage in the textile industry at process temperatures below 180° F (refer to Table I). Therefore, it appears likely that the industry would first look into the recovery and utilization of in-plant waste heat before any serious consideration is given to the use of power plant waste heat.

Furniture industry.—Process heat usage in household furniture manufacture (SIC 2511) is for heating make-up air for ventilation and for heating air for drying operations. Air heating does not appear to be a promising candidate for industrial application of power plant waste heat because of the unfavorable economics of heating air with relatively low-temperature water.

Pulp and paper industry.—The paper industry ranks among the top four users of process heat. The other three industries are primary metals, petroleum refining, and chemicals. Large quantities of process heat are utilized in the pulp bleaching operation at temperatures around 150° F in pulp mills (SIC 2611), paper mills (SIC 2621), paperboard mills (SIC 2631), and building paper and board mills (SIC 2661). The process heat usage for this operation is substantially greater than any other applications of low-grade heat found in this study. The process heat for the bleaching operation is supplied by low-pressure steam (40 to 65 psig).

There are two important factors working against the potential application of power plant waste heat in the paper industry. First; in a pulp mill or an integrated pulp and paper mill, electricity is usually generated at the plant site, especially in the kraft process in which most of the bleaching operations are carried out. In these plants, exhaust steam is taken from the generating turbines as low-pressure steam for process heat requirements. Process steam is also generated from chemical recovery operations and from bark boilers. Secondly, a large quantity of low-grade heat is already wasted in the present pulp and paper mill operation. The waste heat is contained in 100°F to 120°F water, which is comparable in temperature to power plant condenser cooling water. The quantity of this water is estimated at 37,000 gallons per ton of paper product manufactured, [7] which is equivalent to 2.22×10^{12} gallons per year based on 60 million tons of paper product manufactured annually in the United States.

The sensible heat that could be extracted from this water with a 20°F drop in the water temperature, for example from 120°F to 100°F, would be 360×10^{12} Btu/yr, which is more than twice the process heat requirement for the bleaching operations, provided this waste heat is suitably augmented to the process temperatures as needed. Therefore, it appears highly unlikely to find a market for power plant waste heat in the pulp and paper industry.

Chemical industry.—The chemical industries with significant usage of process heat at process temperatures less than 180°F include: alkalies and chlorine (SIC 2812) and synthetic rubber (SIC 2822). The total estimated usage for these two industries in the temperature range indicated is 15.4×10^{12} Btu/yr for the U.S. (Table I).

In the chloralkali industry, the process heat in the indicated temperature range is used for heating the brine in the diaphragm-cell operation. As indicated in Table I, the process heat usage for this application is estimated at only 5 percent of the total process heat requirements. Therefore, this application does not appear promising for importation of power plant waste heat.

The application in the synthetic rubber industry is in the cold SBR (styrene-butadiene rubber) process. The bulk of this heat is used in the monomer recovery operation which is carried out in the range of 120°F to 140°F. Monomer recovery is carried out by steam stripping, which involves direct injection of a low-pressure (15 psig) steam into the process liquid. It is unlikely that such steam could be generated from augmentation of power plant waste heat. There are other minor uses for heating various materials in SBR manufacture, but the total usage is insignificant.

Concrete block manufacture.—In the concrete block and brick industry (SIC 3271), large quantities of hot water at temperatures around 165°F are used in the manufacture of concrete blocks. The hot water is used in the curing process. The process heat consumption for the curing operation is estimated at about 69 percent of the total process heat requirement in concrete block manufacture, which is a significant fraction. This industry appears to be a good candidate for application of power plant waste heat.

Iron and steel foundries.—The foundry industries with significant usage of process heat at temperatures below 180°F include: gray iron foundries (SIC 3321), malleable iron foundries (SIC 3322), steel investment foundries (SIC 3324), and miscellaneous other foundries (SIC 3325). The applicable process heat usage is for heating pickling baths at temperatures in the range of 100° to 212°F. The process heat consumption for the pickling operation is about 35 percent of the total process heat requirement in foundry operation, which is a significant fraction.

The foundry industry seems to be a potential candidate for large-scale application of power plant waste heat. However, the possibility of waste heat recovery in the foundry operations must be examined before the potential application of power plant waste heat could be realistically assessed.

Automobile and truck manufacture.—Significant users of process heat at temperatures below 180° F include: automobile manufacture (SIC 3711) and truck manufacture (SIC 3712). The usage of this heat in the U.S. is estimated at 30.3×10^{12} Btu/yr. Of this, 17.3×10^{12} Btu/yr is used for air heating, which is not considered practical for industrial application of power plant waste heat. The remaining 13.0×10^{12} Btu/hr is used for heating hot water used for parts cleaning and for heating aqueous solutions used for treating metal surfaces for painting. The latter application accounts for about 28 percent of the total process heat requirement and, therefore, would be a potential candidate for application of power plant waste heat.

RESIDENTIAL USES

Assessment criteria

In evaluating the applicability of the heat contained in power plant condenser cooling water, typical yearly electricity demands on a per capita basis can be related to similar comfort conditioning demands. This normalized basis provides a simple correlation between the quantity of heat available in the condenser cooling water and the heat flow requirements into the service hot water, into the house for heating, and out of the house for air conditioning. Both quantity and quality must be assessed for these functions. Where the quality of condenser cooling water is inadequate (too low a temperature) augmentation schemes must be used.

Comfort Conditioning Characteristics

A convenient characterization of a mixed residential/commercial community of 21,500 people requires 3 MW–hr/yr/person for all hot water services. The related heating requirement is 6 MW–hr/yr/person, and, for air conditioning, 4 MW–hr/yr/person must be removed from the buildings. If it is assumed that 8 MW–hr/yr/person of electrical energy is generated for all uses, the condenser cooling water would contain about 13 MW–hr/yr/person, depending upon the industrial mix and the average heat rate.

Typical hot water heating characteristics are illustrated in Figure 1. The condenser cooling water is assumed to leave the power plant at 120° F and return at 100° F. As shown in Figure 1, water from the mains at 60° F must be heated to about 130° F for storage in the tank. Further temperature boost to 150° F (for dishwashing, for instance) is left to resistance heating in the specific appliance. Only about one-third of this energy can be supplied as preheat from the condenser cooling water. The remaining hot water heating requires an augmented energy source. Heating of hot water is reported to be a relatively steady demand spread over about 17 hours of a day.

Comfort heating can be illustrated by the forced hot air example in Figure 2. Only about half the normal air temperature rise can be supplied by a heat exchanger containing a flow of condenser cooling water. The remaining energy requires augmentation. Comfort heat not only has the obvious seasonal swings, but has daily variations dependent upon such things as activity, people density, and infiltration and ventilation. Air circulation power is a significant cost and a modulating heat source can lead to savings through modulated air flows.

Comfort cooling involves a flow of energy from the conditioned space, removed by a cold coil operating at 40-50°F for humidity control. The heat is rejected at temperatures similar to those of the condenser cooling water. The air conditioner condenser provides the same function as the power plant steam condenser and merely adds to that waste heat supply. The energy to drive a vapor compression air conditioner is electricity from the power plant. Heat-driven absorption devices require a source of heat greater than 175°F and generally in the neighborhood of 200°F as shown in Figure 3. Although nonstandard, thermally driven machines operating from 150°F may eventually be developed, condenser cooling water at 120°F is useless as thermal motivation for absorption systems. Since the condenser cooling water and the air conditioner reject heat are at about the same temperature level, any other conclusion borders on "perpetual motion" violation of the second law of thermodynamics.

AUGMENTATION SCHEMES

Augmentation to supply extra energy to power plant waste heat can be either thermal augmentation of thermodynamic. As shown in

Figure 4, thermal augmentation merely means the supply of heat from a second source. Solar heat, a separate burner, or resistance heating would all supply energy at temperature levels high enough to complete the desired heating function—such as the fluid heating of air in a forced air system.

Thermodynamic augmentation takes "available" energy (such as shaft work obtained from an electric motor) to drive a thermodynamic cycle that increases the temperature level. Such a classical heat pump cycle accepts a work input so that heat is accepted at one temperature and the total energy is rejected at a higher temperature. Figure 5 shows that additional energy from the condenser cooling water can be combined with the electrical energy to the compressor drive and the sum is rejected from the heat-pump condenser to finish the heating of "forced hot air", for example.

A related thermodynamic augmentation can be achieved by raising the back-pressure at the power plant condenser, thus raising the condenser cooling water temperature. Figure 6 illustrates this to show that the steam turbine power lost by raising the condenser pressure acts just like a "heat pump" built into the power plant. If all uses for this rejected heat are alike and can fully use this "heat pumped" product, this is the thermodynamically superior approach. In addition, Figure 6 implies that the temperature rise of the condenser cooling water can be increased. A higher water temperature rise leads to proportionately reduced water flow, reducing piping size (cost) and pumping power.

However, load management of the uses of condenser cooling water is apt to be far from perfect. Individual heat pumps, therefore, can be more flexibly applied to the users' demands, can use normal waste heat directly (without augmentation) wherever possible, can be used in a variety of systems, and can even mix heating and cooling of the condenser cooling water, permitting other waste heat sources to be shared.

SAMPLE ECONOMIC EVALUATION

To give comfort conditioning a realistic perspective, an example case will be discussed, concluding with the true "bottom line": Can the use of power plant waste heat be cost competitive? Although the example is somewhat simplified, it shows the major aspects of the use of condenser cooling water and their approximate cost impacts.

Assume that the cooling water leaves the power plant at 120° F and returns at 100° F, maintaining a typical summer condition year round. Only comfort heating and hot water heating will be considered. Both direct heating from the condenser cooling water and heat pump augmentation will be considered. The forced air "furnace" will contain two coils, one containing a controlled flow of condenser cooling water and the second containing a controlled flow of water from a high-temperature storage tank. Low rates of heat delivery will involve only the low-temperature coil (using condenser cooling water), and a low fan-speed setting. At high rates of heat delivery, both low- and high-temperature coils will be active. The fan would be at a higher speed, forcing air flow across the two coils in series. Such a modulation scheme should accrue significant savings in fan drive energy.

The high-temperature coil will be supplied from water in a holding tank heated by the heat pump to about 135° F. The heat pump source is the condenser cooling water from the power plant.

This hot water holding tank also contains a coil for the service hot water, finishing the hot water heating. Service hot water initially passes from the water main to a small buffer tank maintained at about 110° F by a heat exhanger containing condenser cooling water.

Having defined a sample system, it is now possible to estimate a general yearly energy use on a per capita basis. Of the 3.0 MW-hr/yr/person used for water heating,

Direct supply from circulated cooling water	1. 0
Indirect supply as a heat pump source	1. 5
Subtotal	2. 5
Electrical energy to drive the heat pump	0. 5
Total, (MW-hr/yr)	3. 0

For the comfort heating total of 6.0 MW-hr/yr/person,

Direct supply from circulated cooling water	2. 0
Indirect supply as a heat pump source	3. 0
Subtotal	5. 0
Electrical energy to drive the heat pump	1. 0
Total (MW-hr/yr)	6. 0

This means that 7.5 MW-hr/yr/person is recovered from the condenser cooling water and 1.5 MW-hr/yr/person is supplied as electrical energy for the heat pump. No charge will be made for the air circulating fan power, assuming both this system and the reference "clean fuel" system would require the same power.

The economic viability of the condenser cooling water system is evaluated by estimated the cost of the "clean fuel" that it replaces. The local distribution loop is based on a community of 21,500 people described by Aamot, [8] located 15.5 miles from the power plant. The yearly costs on a per capita basis are:

(1) Heat pump electricity+32mills/kW-hr	$48
(2) Supply line capitalization (10% per yr)	42
(3) Local distribution piping (10% per yr)	12
(4) Individual heat pump system (10% per yr)	30
(5) Condenser cooling water pumping costs	4
Total (per year per person)	136

If we assume a 60 percent fuel efficiency for the reference heating system,

$$\frac{7.5+1.5}{0.6}=15 \text{ MW-hr/yr/person}$$

is the yearly fuel supply. Converting this to a conventional heating value leads to a break-even fuel cost of

$$\frac{(\$136)}{(15 \text{ MW-hr})}\times .293\frac{\text{MW-hr}}{10^6 \text{ Btu}}=\$2.66/10^6 \text{ Btu}.$$

Since this is in the neighborhood of projected, near-term clean fuel costs, the use of condenser cooling water appears to be economically feasible. The system above is approximate and each case needs individual detailed evaluation. Cases with shorter pipelines shared by larger communities will be more attractive; others will be more marginal. But the overall results should be attractive.

Significant flexibility in system design and in implementation exists. The "community" serviced in the above example is relatively small and involves the rejection heat from only about 30 MW of capacity at a 65 percent capacity factor. Condenser waste heat is fully used only in the winter and agricultural or industrial uses other times in the year are not considered. Rejection of the air conditioning load to this cooling water loop could increase the coefficient of performance of some of the individual air conditioner compressors, thus reducing the summer electricity costs.

More advanced concepts include technological approaches similar to those developed for solar energy. For instance, increased local storage could result in limiting heat pump compressor operation to off peak hours, reducing energy cost to the user, and providing load leveling to the utility. Integration with solar systems is also possible.

CONCLUSIONS AND RECOMMENDATIONS

The use of power plant waste heat in industrial processes at application temperatures below 100° F appears to be limited. Therefore, the direct use of waste heat without temperature augmentation appears most promising for preheating applications.

In the temperature range up to 140° F, the food processing industry appears to be the best candidate for application of power plant waste heat.

In the temperature range up to 180° F, possible candidates include: food processing, concrete block manufacture, automobile manufacture, and iron and steel foundries.

It appears that a significant market exists for potential application of power plant waste heat, provided it is augmented for process temperatures in the range of 140° to 180° F. In order to determine the economic feasibility, a survey of the identified industries in a specified region and a cost analysis are recommended.

Comfort heating and hot water heating appear to be economically feasible uses through district heating systems using power plant waste heat. In addition,

(1) Augmentation is required;
(2) Heat pump augmentation is preferred;
(3) Black-pressure augmentation at the power plant need only maintain the summer discharge temperature throughout the year;
(4) Flexibility and growth potential exist as systems can be tailored to individual service areas;
(5) Initial service areas can be small.

It is recommended that a specialized district use model be developed. The model should be so arranged that distribution network costs can be estimated initially for a "hypothetical" district and subsequently for a real district. In addition, a marketing strategy should be developed to add convenient industrial uses to complement district heating.

In summary, as fuel prices rise, society will continue to need increasing amounts of central station electricity, but due to equally important needs for low cost energy, central station power plants may get smaller and become better integrated into high-density population regions of our country, as they were almost a century ago.

ACKNOWLEDGMENTS

This paper is primarily based on a recent study carried out by Battelle for the Tennessee Valley Authority on a Technical Assessment of Industrial Processes and Residential Uses of Power Plant Waste Heat. Dr. Gerald A. Hollinden recommended that Battelle might provide an independent assessment of this opportunity for possible technological improvement. The program monitor was Dr. L. Barry Goss. We are grateful for support of the program and permission to publish the results. Internal review of this manuscript by F. Jere Bates, who leads Battelle's current efforts for Toledo Edison on specific applications of waste heat in their generating territory, is also appreciated.

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TABLE I.—U.S. PROCESS HEAT REQUIREMENTS IN TEMPERATURE RANGE UP TO 180° F (1974) (9, 10)

SIC code and industry	<180° F, 10^{12} Btu/yr	Industry total, 10^{12} Btu/yr	Percent of industry total
2011 Meatpacking plants	11.4	21	54
2013 Sausages and other prepared meats	44.9	46.4	97
2016 Poultry dressing plants	3.16	3.16	100
2022 Cheese, natural and processed	4.80	15.0	32
2023 Condensed and evaporated milk	5.20	12.25	42
2026 Fluid milk	1.44	1.44	100
2034 Dehydrated fruits and vegetables	.47	9.29	5
2046 Wet corn milling	3.96	18.42	21
2051 Bread, cake, and related products	.84	7.24	12
2062 Cane sugar refining	1.03	35.12	3
2063 Beet sugar	4.63	64.82	7
2075 Soybean oil mills	4.05	16.41	25
2079 Shortening and cooking oils	.84	2.48	34
2082 Malt beverages	1.13	15.82	7
2086 Bottled and canned soft drinks	2.43	2.43	100
2261 Finishing plants, cotton	32.2	146.1	22
2262 Finishing plants, synthetics			
2281 Yarn and thread mills	25	150	17
2435 Hardwood veneer and plywood	.6	7.0	9
2436 Softwood veneer and plywood	2.9	67.9	4
2511 Wood household furniture	9.5	9.5	100
2512 Upholstered household furniture	2.3	2.3	100
2611 Pulp mills	175	1,071	16
2621 Paper mills			
2631 Paperboard mills			
2661 Building paper and board mills			
2812 Alkalies and chlorine	10.0	203	5
2819 Industrial inorganic chemicals (borax)	.86	3.5	25
2822 Synthetic rubber (cold SBR process)	5.36	10.6	51
2841 Soap and other detergent	.86	1.19	72
3111 Leather tanning and finishing	2.51	2.51	100
3211 Flat glass	7.98	338	2
3221 Glass containers			
3229 Pressed and blown glass, nec			
3231 Products of purchased glass			
3271 Concrete block and brick	12.29	17.71	69
3273 Ready-mixed concrete	.34	.34	100
3321 Gray iron foundries	151	431	35
3322 Malleable iron foundries			
3324 Steel investment foundries			
3325 Steel foundries, nec			
3331 Primary copper	14.2	72	20
3479 Metal coating and allied services	.011	.025	44
3711 Motor vehicles and car bodies	30.3	46.6	65
3713 Truck and bus bodies			
Total	574	2,852	----------

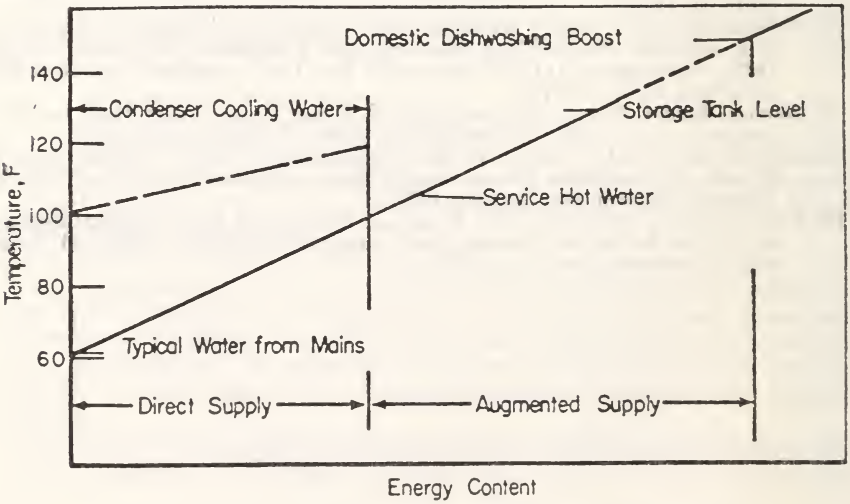

FIGURE 1. SERVICE HOT WATER CHARACTERISTICS

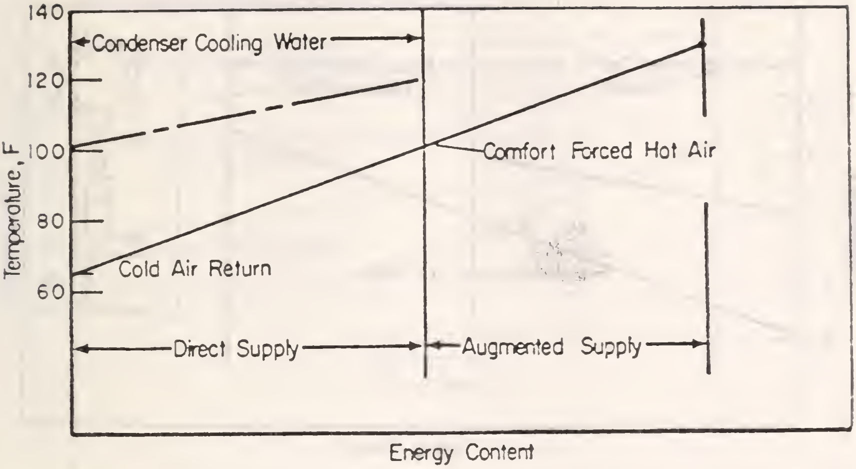

FIGURE 2. TYPICAL FORCED HOT AIR HEATING

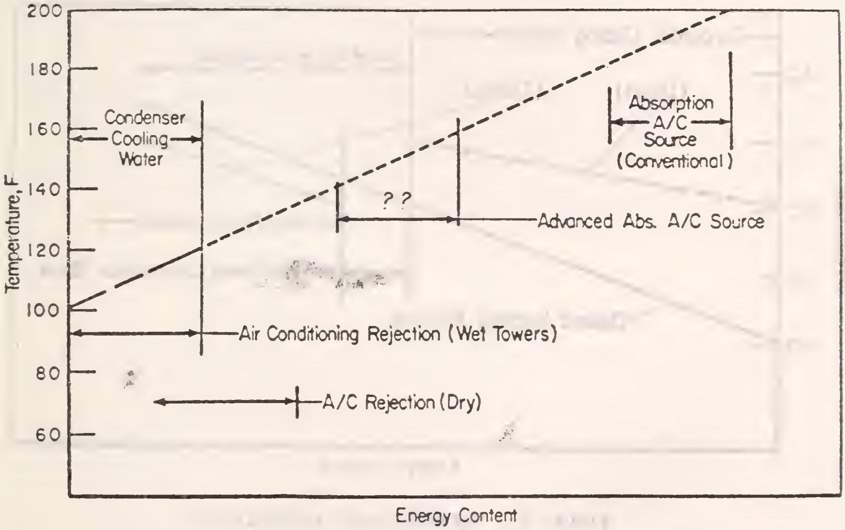

FIGURE 3. AIR CONDITIONING HEAT EXCHANGE CHARACTERISTICS

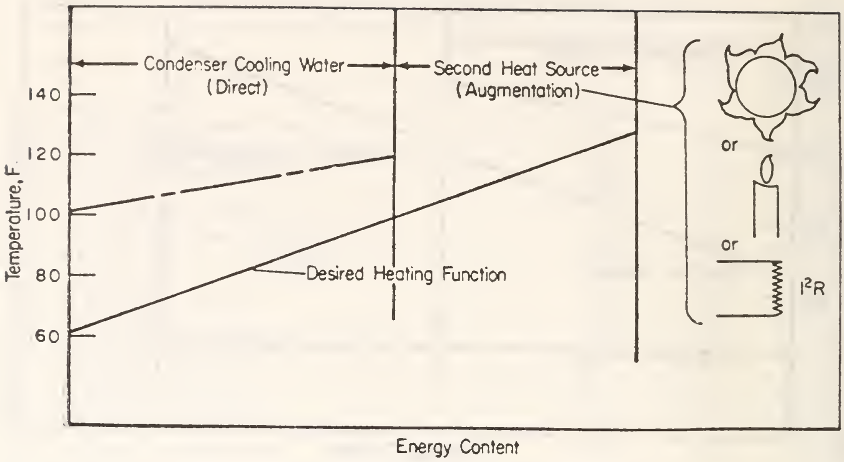

FIGURE 4. THERMAL AUGMENTATION

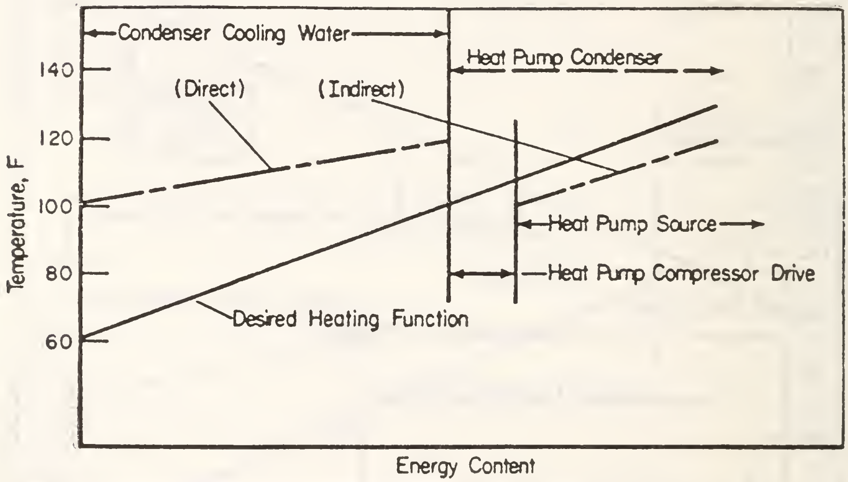

FIGURE 5. THERMODYNAMIC AUGMENTATION

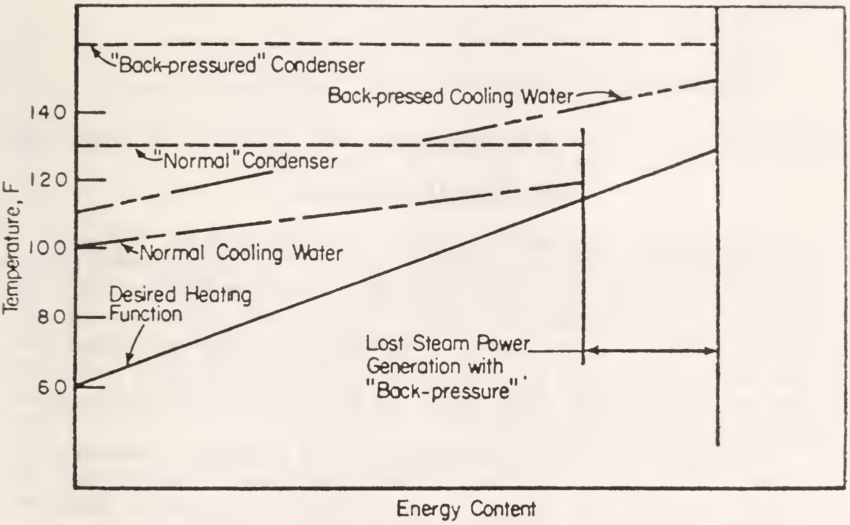

FIGURE 6. BACK-PRESSURE (THERMODYNAMIC) AUGMENTATION

CONSERVATION—I

(By John H. Gibbons)

Conservation is a major means of dealing with the complex and sometimes conflicting demands involved in the syndrome of factors that make up what is called the energy problem. The next selection discusses one aspect of conservation: the potential for more efficient use of energy, stimulated in part by anticipated increases in the price of energy relative to the cost of other goods and services. On that assumption, as the article indicates, much progress appears possible.

Actions to increase the efficiency of use of energy are generally taken at the manufacturing or industrial level. Energy price factors are felt more directly in this sector, and industrial firms are more able to obtain the capital needed for generally more expensive energy-efficient equipment, as well as more likely to appreciate the advantages of making such capital investments. Even increasing the energy efficiency of consumer goods depends on the initiative of the industrial sector.

Conservation at the individual level is more a matter of merely doing less—changing life styles in response to price and availability. This is so in spite of the obviously essential role of the consumer in buying more energy efficient goods. Since price has a major importance in such decisions, it is significant that retail prices of energy have not increased since 1973 nearly as rapidly as wholesale prices; indeed, to a large degree they have increased little relative to the price of other goods and services. Thus the pressure to conserve energy at the individual level has been much less pronounced than it has been at the industrial or commercial level.

LONG TERM PROSPECTS FOR ENERGY CONSERVATION*

(By John H. Gibbons, Director Environment Center, University of Tennessee, Knoxville, Tenn.)

(A) INTRODUCTION

Even a cursory examination of energy utilization today anywhere in the world discloses the fact that the efficiency of use is generally very remote from theoretical limits. There are good reasons for this situation to exist today but equally good reasons to embark on a long term course to very much higher energy productivity. The purpose of this paper is to briefly review the long-term opportunities for higher energy productivity and the impediments or limitations to the extent and rate at which this higher productivity can be reached. While the focus is on the U.S., the general principles can also be applied to other societies.

In addressing the need and likelihood for more productive energy use in the future several assumptions held by the author, but shared by many others, should be made explicit:

1. The price of energy, compared to other goods and services, will be substantially higher than present. However, except for relatively short term and emergency situations, real energy price will probably never be more than about four times higher than present price,because at that price level, given time, extremely large quantities of renewable and long-term sustainable energy resources are economic. In the long term, we will not run out of energy—but we are rapidly running out of cheap energy. It is not uulikely that gas and oil prices (in real terms) will be double present prices by 2000.

2. The dominant forms of energy will be the same as today: electricity, gas, and liquids (albeit derived from a variety of sources, increasingly non-fossil in origin).

3. As energy prices rise it will pay to alter patterns and efficiencies of energy use, substituting technological ingenuity and institutional innovation for energy resource consumption.

(B) LIMITATIONS TO ENERGY PRODUCTIVITY [1]

(1) *Natural law.*—While energy is always conserved, it becomes less useful after each time we use it. For example, when natural gas is used to heat water *no* calories are lost, but the inherently very useful calories stored in the gas are converted to hot water and waste heat and in their new form they are far less "available" to do work. As energy gets more expensive the technologist designs machines that cause smaller amounts of high availability energy to be used for a given service rendered. The technologist also tries to match the quality of the energy source to the quality of energy needed to perform a service so that minimum "availability" is lost.

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*Paper presented at the International Scientific Forum on An Acceptable World Energy Future, Miami Beach, Florida, November 27-December 1, 1978.

[1] See Gibbons, J. H., "Long Term Research Opportunities", a chapter in "Improving the Energy Productivity of the American Economy", ed. by John Sawhill (Prentice Hall, 1979) to be published.

The maximum efficiency of any cyclical process (e.g., a heat engine such as a steam boiler) is related to the combustion temperature, T_H and the coolant (discharge) temperature, T_C. Well over a century ago Carnot showed theoretically that the *maximum* efficiency, E, is : $E = 1 - (T_C/T_H)$. Clearly, unless the combustion temperature is extremely high and/or the discharge temperature extremely low, efficiencies are relatively small. It is possible using fossil fuels to generate combustion temperatures that result in very high efficiencies (fossil fuels, with air combustion, can burn as hot as 3000°F) but there are no materials that can readily be used to contain the steam above about 1300°F. Such limitations in a power plant can be overcome by using a combined cycle wherein a "topping" cycle consisting, for example, of a gas turbine followed by a steam cycle is used. Even by combining such methods one is still practically constrained to maximum Carnot efficiencies of less than 70 percent, with 30–40 percent actually attained for modern electricity generation plants.

While most heat pumps and air conditioners provide about twice as much heating or cooling energy as input energy by extracting heat from outside air, or dumping heat into the outside air, they could *theoretically* supply about twenty times as much (hence they have an actual efficiency of less than 10 percent of Carnot efficiency). Equipment could be made with much improved energy efficiency and still be much lower than Carnot's limit but each improvement in efficiency requires more investment (e.g., a more efficient heat radiator). Some typical Carnot efficiencies are listed in Table 1.

Since a large fraction of uses of energy actually only require relatively low temperatures* it is clear that thermodynamic *matching* between energy sources and energy uses holds much promise. In other words, much better thermodynamic utilization can be obtained through a variety of techniques including total energy systems, cascaded energy use such as cogeneration, and low temperature storage.

Table 1.—Second law efficiencies for some energy-consuming activities

Sector	*Carnot efficiency (percent)*
Residential:	
Space conditioning:	
Furnace, heat pump	5. 0
Electric resistance	2. 5
Air conditioning	5. 0
Water heating:	
Gas	3. 0
Electric	1. 5
Refrigeration	4. 0
Transportation:	
Automobile	10. 0
Industry:	
Electric power generation	33. 0
Process steam production	34. 0
Steel production	23. 0
Aluminum production	13. 0
Average manufacturing	13. 0

Selected sources:

(1) M. H. Ross and R. H. Williams, Bulletin of the Atomic Scientists November 1976, page 33 ff.

(2) G. N. Hotsopoulos, E. F. Gyftopoulos, R. W. Sant, and T. F. Widner, Harvard Business Review (March–April, 1978, pg. 111ff).

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*30% of all U.S. fuel and electricity is used for tasks which change temperature by less than 80°C; another 15% produces steam at less than 400°C.

It is conceivable that some of the same goods and services now provided by heat engines can be provided by some other mechanism. If so the Carnot efficiency limits could be by-passed. For example, an electric motor powered by a chemical battery might be used to replace an internal combustion engine to power a car. These electrochemical reactions are not limited by Carnot's heat engine laws and can operate with very high efficiency. However, in thinking about such substitutes we must remember that other constraints will operate. For example, the electricity to recharge the battery must be generated somewhere, likely in a Carnot-limited device. Of course, it is possible that electricity could be generated from fuels via a hydrogen-oxygen fuel cell and again avoid the limitations of efficiency imposed on a thermal process. But where do the hydrogen and oxygen come from?

Other limitations to efficiency of energy-consuming devices that are imposed by natural law include properties of materials such as heat conductivity, friction, and high temperature strength. For example:

> A large fraction of energy required to power a car or truck above 60 mph is due to wind resistance and rolling friction between the tires and the road;
>
> The efficiency of a refrigerator, freezer, or air conditioner is strongly dependent upon the heat transfer properties of the heat exchanger which dumps heat into the outside air;
>
> The efficiency of high temperature, high pressure combustion devices are limited by the loss of mechanical strength of materials at high temperature;
>
> The finite resistance to heat transfer through insulating materials limit the conservation design in appliances, homes, and industrial processes where we wish to hold heat in—or out.

(2) *Technology.*—One of the most fundamental challenges to improving energy productivity lies in improvement of various properties of existing materials and processes, and development of new materials and processes with desired special characteristics. As scientific understanding of the properties of materials grows we have already witnessed profound impacts on technology and, in turn, on the amount of energy required to provide a given amenity (examples are given later in this paper).

In virtually all instances of improved energy productivity the notion of saving energy has been an important but not necessarily dominant one in spurring development of the processes. Indeed, many of these developments occurred while energy prices were falling. More important in inducing the developments has been the drive to improve overall quality, cost and reliability of product. Another very significant factor has been the desire to improve the yield of final product compared to the consumption of raw materials. Major advances in energy-efficiency have occurred over the past several decades but some (e.g., conversion of coal-fired steam locomotives to diesel electric drive) were achieved at the cost of switching to less plentiful fuels. Nevertheless, close consideration of virtually every major energy-consuming activity reveals major opportunities for energy to be replaced by technological advances.

(3) *Economics, complexity, and interdependence.*—As nations industrialize and urbanize, their citizens seem to accept conditions of in-

creasing socio-economic and technical complexity in exchange for material benefits. The U.S. economy is now remarkably complex and interdependent, in large measure because increased scale of operations (e.g., farming, communications, power production, transportation) tends to decrease unit production costs. Of course, at the same time this trend tends to have undesired but "external" side effects such as requiring workers to commute farther (at their own expense).

In the case of energy the "waste" from one user (e.g., a power plant) can be used as the "input" energy for another (e.g., heat for an apartment building). Similarly the purchased energy required to provide space conditioning in a house can be considerably decreased by installing a complex automatic electronic sensing and control system; or, transportation energy for urban commuter traffic can be drastically lowered by extensive use of carpools and vanpools. There are three conditions that tend to govern the extent to which these kinds of conservation tactics are attractive:

a. *Energy price.*—As energy gets relatively more expensive, increased complexity and interdependence, if a large improvement in energy productivity results, become more tolerable.

b. *Reliability.*—We tend to accept complexity and interdependence more readily when the system can be counted on to operate without unwanted interruption. An apartment owner is not interested in being heated by "waste heat" from a power plant that cannot be counted on to operate reliably throughout the heating season. Improvement in reliability can be expected to continue to result from investments in science and technology; however, consumers are increasingly suspicious of complexities and big technology.

c. *Proximity and scale.*—Because of the past performance of energy price, economies of scale in industry, and land use patterns of residential and industrial development, there are not many major opportunities for energy savings through increased interdependence in our *existing* system. Present sources of low grade and waste heat, sufficient to heat and cool buildings, are generally sited too far from existing buildings to justify construction and transport costs of the heat. The extremely large size of most power plants cause so much waste heat to be generated that markets within plausible range are oversaturated. As new capital investments are made, much improvement could be gained from energy-conscious siting and sizing of energy production and other industrial plants.

d. *Convenience.*—Citizens, be they individual or corporate, value independence. A petrochemical plant manager might save fuel bills by accepting waste heat from a power plant but his hidden costs in doing so include threat of regulation, unscheduled interruptions, and inflexibility in future negotiations for fuel purchases. An urban commuter can save money in joining a vanpool but in doing so must forego the freedom that would otherwise be available in driving his own car. An auto driven at 55 mph might get 20 percent better mileage than one driven at 70 but the occupant who highly vlaues his time may choose the faster speed despite the losses in fuel and safety. A refrigerator with a certain color may be more important to a buyer than the fact that it uses half again as much electricity as one of another color. Thus "convenience" and independence can be strong factors in limiting energy productivity.

e. *Economics.*—While the U.S. markets of energy production and energy-utilizing equipment (producers and consumers) are not "free" they are competitive. Therefore as energy prices and availability change all of these factors adjust to maximize their welfare. In the past and to a large extent still today the energy characteristics of consumer goods are either invisible or poorly visible at point of sale, even for items (e.g., refrigerators) where the energy costs to operate over its lifetime will considerably exceed the purchase price.

With upward trending energy prices the wise energy user will make purchase decisions that take account of projected future cost of energy as well as current prices. There are at least three reasons why this situation generally doesn't obtain. First, energy costs are poorly visible, especially on new goods. Second, future energy prices are uncertain and subject to political and cartel manipulation. Third, in a period of high inflation we tend to pay less attention to future expenditures than present expenditures. This last situation is particularly important for poor people because this effective discount rate used in capital investment decisions (e.t., 50 percent per year for those with incomes of less than $5,000 per year) is several times higher than the rate used by middle class.

Thus the relative lack of access to capital markets by many energy consumers, combined with lack of clear signals about present and future prices and a time of substantial inflation all tend to frustrate a shift from energy purchases over to capital investment in more energy-productive stock.

(C) WHAT CAN BE DONE?

There are now ample examples of the reality of substitutibility of technological and managerial sophistication for energy consumption throughout the world's economics, and especially in the U.S. Therefore rather than a comprehensive review we only relate a few examples to illustrate not only what *can* be done but also what is *being* done.

(1) *Transportation.*—Automobile mileage can be doubled for less than a 10% increase in purchase price.[2] However, considerable time (e.g., 7 years or more) is reasonably required for a production changeover.

While the new cars will have less capability to leave rubber on the road from high acceleration they will otherwise provide the same comfort, safety, and performance. Similar major improvement in energy productivity can accrue in new production of trucks and airliners. Beyond these purely technological changes, intermodal shifts of freight and urban/commuter mass transportation can provide substantial further improvements.

(2) *Buildings and appliances.*—As for the automobile there are a lengthy string of options to radically improve energy productivity in this sector. Energy-consciousness in design (e.g., orientation of building, location of windows and use of internal thermal mass, proper overhanging eaves) can make a major impact of itself. The construction of the thermal envelope (shell) can cut heating requirements dramatically for minor changes in construction cost (Table 2, Figures 1, 2). Finally the design and operation of the space and water heating, cooling, ventilation, and lighting system can have a major impact upon requirements for purchased energy (Figure 3). A caveat must be added: As

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[2] Gibbons, et al, *Science 200*, 142 (April 14, 1978).

the thermal envelope and passive solar effectiveness are improved the amount of purchased energy required becomes so small that one cannot justify capital-intensive, highly energy-efficient heating and cooling systems.

Table 2.— *List of design options and associated additional feature for increasingly energy-efficient thermal envelope of a residence (key to figures 1 and 2)*

Design option	*Added feature*
1	Baseline.
2	R–11 attic insulation.
3	R–11 wall insulation.
4	R–19 attic insulation.
5	R–11 floor insulation.
6	Storm windows.
7	R–30 attic insulation.
8	R–19 floor insulation.
9	2-paned SGD.
10	R–13 wall insulation.
11	R–38 attic insulation.
12	R–19 wall insulation.
13	3-paned windows.
14	R–49 attic insulation.
15	Storm door.
16	R–23 wall insulation.

Source: E. Hirst and P. Hutchins, Engineering-Economic Analysis of Single-Family Dwelling Thermal Performance, Oak Ridge National Laboratory Report ORNL–CON–35 (1978).

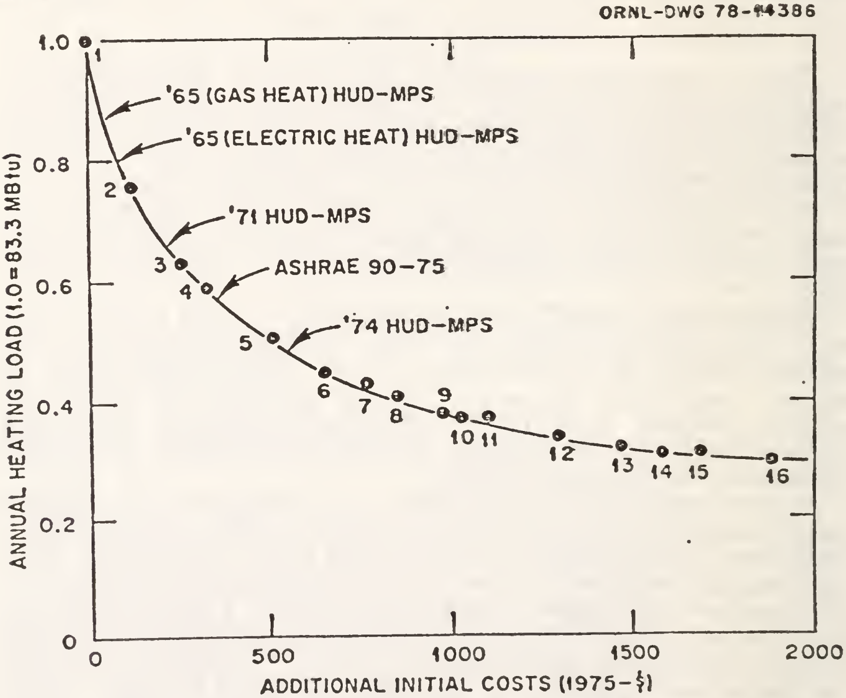

Figure 1.—Heating/cooling load vs incremental cost for a new single family residence in weather conditions equivalent to Kansas City. The numbers refer to options described in table 2. The arrows point to loads that correspond to various indicated codes and standards.

Source: E. Hirst and P. Hutchins, "Engineering-Economic Analysis of Single-Family Dwelling Thermal Performance," Oak Ridge National Laboratory Report ORNL–CON–35 (1978).

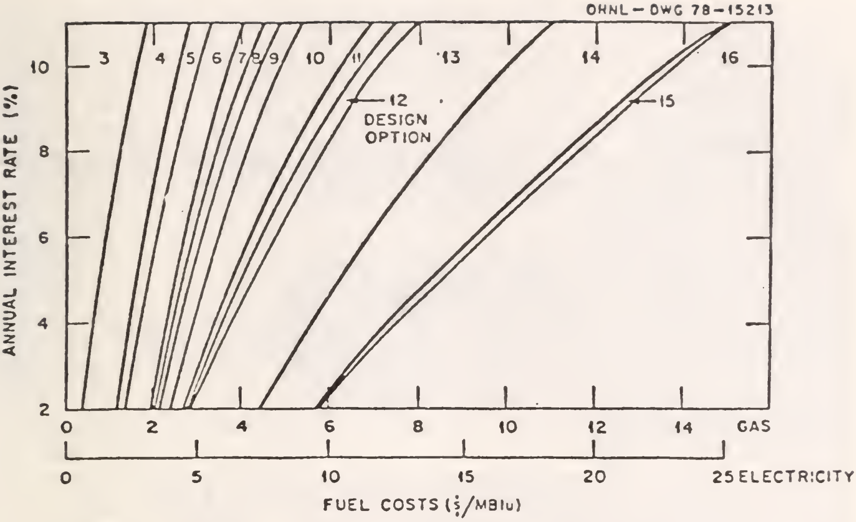

Figure 2.—Sentivity of option selection to assumed annual discount (interest) rate and fuel costs. See table 2 for description of options and Figure 1 for energy-intensiveness.

Source: E. Hirst and P. Hutchins, Engineering-Economic Analysis of Single-Family Dwelling Thermal Performance, Oak Ridge National Laboratory Report ORNL-CON-35 (1978).

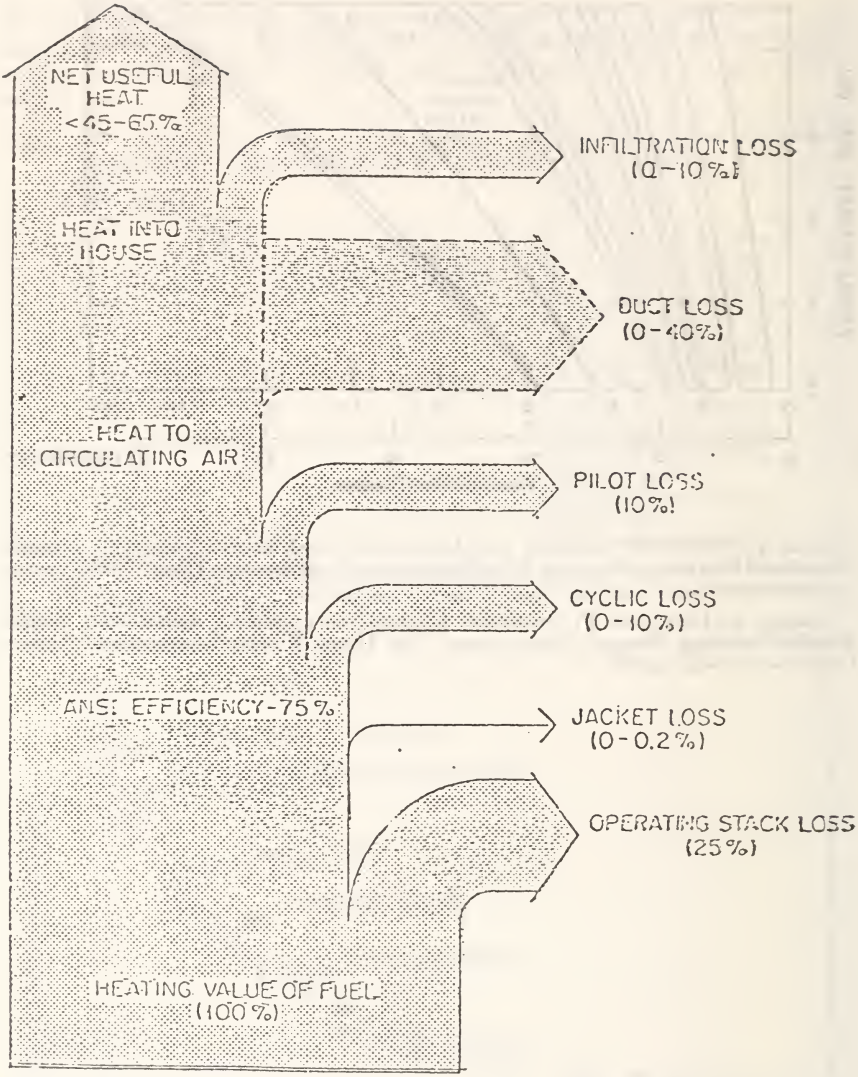
NET USEFUL HEAT <45-65%
HEAT INTO HOUSE
HEAT TO CIRCULATING AIR
ANSI EFFICIENCY-75%
HEATING VALUE OF FUEL (100%)
INFILTRATION LOSS (0-10%)
DUCT LOSS (0-40%)
PILOT LOSS (10%)
CYCLIC LOSS (0-10%)
JACKET LOSS (0-0.2%)
OPERATING STACK LOSS (25%)

FIGURE 3.—Energy flow for a furnace system.

Source: E. C. Hise and A. S. Holman, "Heat Balance and Efficiency Measurements of Central Forced Air Residential Gas Furnaces" Oak Ridge National Laboratory Report ORNL–NSF–EP–88, October 1975.

In short, the application of only modestly sophisticated energy-sensitive design and engineering principles can cut overall purchased energy requirements in half or less. Numerous instances of such improvements have occurred over the past five years. Results are especially impressive for larger buildings. Eight years ago a typical commercial building required 180,000 TBU/ft² per year. Nowadays the (achieved) design figure is more like 50,000 [3] and the opportunity to make further improvements appears to be substantial. Because of these facts it appears to be quite possible that despite the continued expansion of residential and commercial space in the U.S., total energy requirements in this sector could roughly level out over the next 30 years, or at least not grow faster than about one % per year despite a 30% population increase and a doubling of real GNP.[4]

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[3] Charles Ince, AIA Research Institute (private communication, 1978).

(3) *Industry.*—Carnot efficiencies presently achieved in the industrial sector range from low to impressively high (Table 1). Besides many opportunities for improvements in energy productivity using *existing* processes there are important additional opportunities to develop new processes that can markedly improve productivity. Here are a few examples of recent advances that typify the sorts of things that can continue to happen as we further substitute technological innovation for energy consumption.[2-6]

> The progression from vacuum tubes to transistors and thence to large scale integrated circuits have enabled the energy required for various functions in communications and computers to be reduced about a millionfold in two decades.
>
> The efficiency of electricity conversion into lighting has increased from less than five percent (incandescent) to more than thirty percent (alkali-halide) since 1950.
>
> The energy required to produce a pound of aluminum from alumina has fallen from more than 12 kw-hr/pound in 1950 to less than 5 kw-hr/pound using the new Alcoa molten chloride process.
>
> The energy required to produce low density polyethylene has been halved due to a new process developed by Union Carbide.
>
> Research on producing a fire-safe diesel fuel unexpectedly resulted in a fuel that burns with 10% better economy and 50% less exhaust smoke.
>
> Energy consumed per unit output of product has fallen substantially for all industry over the past decade, as much as 50% for many petrochemical products.

(4) *Behavioral change.*—We have limited the previous discussion to technological innovations and applications. Clearly there are a host of plausible changes in consumer priorities that could have marked impact on energy demand over the next several decades. Such priority changes could push energy demand up or down. One thing is certain: "lifestyles" are always changing. Even in the low GNP growth scenarios studied by the CONAES Panel on Demand and Conservation[2] real income doubles over 35 years and that fact alone implies substantial lifestyle change, especially when combined with major demographic shifts due to lowered birth rates.

If energy prices increase it is likely that consumers, seeking maximum welfare, will shift their behavior toward less energy-intensive activities (e.g., purchase a night setback thermostat, alter indoor space temperatures). Another form of behavior change could (hopefully) become more important in future years in the emergence of an ethic that results in energy savings as a means to share energy resources with other people who live in other places and in future times. The extent to which these accommodations will occur is problematic but even minor changes could have substantial impacts on energy demand.

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[2] Gibbons, et al, *Science 200*, 142 (April 14, 1978).

[4] E. Hirst and J. Jackson, *Energy 2*, 131 (1977).

[5] C. Berg, *Science 199*, 608 (February 10, 1978).

[6] G. N. Hatsopoulos, E. P. Gyftopoulos, R. W. Sant, and T. F. Widner, Harvard Business Review (pg. 111ff, March/April 1978).

(5) *Research opportunities.*[1] The areas of energy utilization are so diverse that the richness of opportunity to improve energy productivity through research is difficult to overestimate. Major public support should be provided not only for basic science, engineering, and social science research relevant to energy utilization, but also for developing the technological capability to use energy at an efficiency that corresponds to energy prices that would obtain from such sources as gas synthesized from coal. It is naturally difficult to anticipate how much this research will contribute to higher energy productivity (that is economically feasible for a given energy price) but my guess is that such research will likely be very productive, in part because the field has received little attention until very recently. The fact that current practice is far removed from theoretical limits also gives strong support to this notion.

(D) LONG-TERM PROSPECTS

After examining in detail the specific prospects to achieve major increases in energy productivity, given several decades of time, it can be concluded that for the U.S. a reap GNP of about twice current level can be achieved without a significant increase in (purchased) energy.[2] The biggest uncertainty is not so much the extent to which energy productivity can increase but rather the time over which such improvements can accrue. Such a situation could result from the vigorous application of human ingenuity, mostly through technology and management. Further shifts toward higher energy productivity could occur as a result of research and/or by altered consumer behavior patterns and lifestyles.

In view of the manifold uncertainties about our energy supply future and the relative ease—if not attractivensss—(e.g., capital requirements, employment and inflation implications) of effecting much higher levels of energy productivity it seems only prudent as national insurance to move ahead in this area with dispatch since decades will be required once we commence.

The things we've concentrated on in this paper probably are more readily associated with "soft" energy paths rather than "hard" paths. For example, the long-term route to higher energy productivity shifts a lot of capital investment from the energy production sector to the energy consuming sectors. It opts for dispersed energy conversion so that productive uses of "waste" heat are easier to capture, consequently it tends to push technology toward smaller scale economy. But it does not seek higher productivity via denial of amenities. Rather it rests upon the reality that human ingenuity, applied through both technological and institutional innovations, can substitute for energy to a major degree.

In this light the "soft" path can be interpreted as a new level of technological and institutional sophistication, adapted by a society that seeks its affluence in a way that is more harmonious with the rest of nature. Such an application of human wisdom could translate the specific issue of "Prospects for Energy Conservation" into a more general one: To what extent can mankind substitute ingenuity for resource consumption? As a consequence our measure of progress could become less that of counting how much material and energy resources we consume and more that of how little we require to provide a given level of amenities.

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[1] See Gibbons, J. H., "Long Term Research Opportunities", a chapter in "Improving the Energy Productivity of the American Economy", ed. by John Sawhill (Prentice Hall, 1979) to be published.

[2] Gibbons, et al, *Science 200*, 142 (April 14, 1978).

CONSERVATION—II

(By Robert A. Herendeen)

The automobile is both a major consumer of energy, and the technology that presents one of the most intractable problems of the energy picture, since it runs, at present, only on oil. As the author of the next selection points out, it also has many negative social and environmental effects.

Nevertheless, as this selection reveals, even in countries where the population is small, the distances travelled short, and individual income by no means excessive, people are buying automobiles and using them. As the discussion also reveals, these decisions are being made on the basis of the short-term values described in the opening essay of this volume: price, convenience, reliability and independence. (See page 6) Other values, such as environment, social values, and conservation of life styles, are recognized but tend to be disregarded or downplayed.

The author's alternative title for this article is: "The Ascendance of the Auto: Another Example of the Tragedy of the Commons."

WHY WE BOUGHT A CAR IN NORWAY

(By Robert A. Herendeen)

Most articles critical of the automobile blast you with terrifying anecdotes and statistics and then implore you to go out and do something. I won't do much of either. I'm willing to bet that you already know, deep down, that the car is strangling America—and that, in the same thought, you have concluded you can't do anything about it.

Neither can I. Neither can anyone acting alone because of the strength of the dynamics of the way people and cars get together. This is all obvious to students of game theory and economics 101, but thanks to having lived in Trondheim, Norway, for two years (1975–77), I've acquired a gut appreciation that transcends all of that. I saw it happening. Against the backdrop of the forests and mountains of the most beautiful country on earth, I even did my part.

This anthropologist's dream opportunity was mine because Norway is about 25 years behind the U.S. in its auto development. In 1975 the ratio of cars to people was 1 to 4—where the U.S. was in 1948, before the Interstate Highway System, Holiday Inns, and Levittown, and while train and bus services were still relatively commonplace. (The U.S. ratio is now 1 in 2.) Only one-half of Norwegians commute by car, versus nine-tenths here.

At first glance it looks as if Norway will do things differently than we did, The societal impacts of "bilism" are widely publicized and discussed. Auto safety inspections are tough and driver training is available only through state-licensed schools at an average cost of $900. In contrast to our condoning of the alcohol-gasoline connection ("Shucks, son, I've had a few too many myself now and then. You drive right on home ahead of me"), the Norwegians come down hard. First offense drunken driving (blood alcohol 0.05%, half the limit in Illinois) gets you 28 days in jail, mandatory. 0.05% can be exceeded with two mixed drinks; hence the famous Scandinavian habit of designating a driver for the night, who then does not drink at all. Public transportation is good (though not cheap); we never lived more than one-third of a kilometer from a bus stop and the buses ran at least every half-hour. Because of taxation, gasoline is $1.70 per gallon, and cars nearly twice as much as here. (Average take-home pay is $7,000 per year). Today there are no cars or trucks manufactured in Norway, which results in a very subdued and flabby auto lobby.

In spite of all these reasons not to have a car, the number is growing at about 7% per year (1975–77), or doubling every 10 years. "Ole Q. Public," headlined the Trondheim *Adresseavis*, "is buying cars as never before." In the 22 months we were there, the number of cars on the road increased by 12%.

What's going on? I'll illustrate by relating three experiences of my wife and me. First, after 6 months of trauma, we bought a car. Second, we worked on a farm in a valley accessible only by boat. Third, we shopped at Trondheim's first American-style shopping center. In the discussion, three general points should be kept in mind:

1. People want cars. Period. If they are fed, the next hierarchial need/want is for reliable, personally controlled rapid transportation. The stated reasons are many, but the result is the same. This conclusion is robust, as they say, over essentially all cultures. This begs the question of why, of course, but I'm an experimentalist. On the basis of observation I accept it as a given, a strong force of nature like gravity. There's no hope of "understanding" it, only of managing it. In America most of us have consumated (but not extinguished) the desire by age 18, but in Norway "auto angst" is still evident in older age groups. Witness the personals in the *Adresseavis:* "Is there a kind and loving man who will help a lonely separated woman? You must have a car." "Retiree seeks contact with an honest, sensitive and loving single woman, 45–60. Have new apartment, nice car." "Woman, 20 years old, with one child, wishes to meet a kind and dependable man. You must be from Trondheim and hopefully have a car." One-third of these ads mention the car explicity.

2. The equilibrium between the car and its competitors is unstable. Increased ridership in cars means less in public transport, resulting in higher fares and reduced schedules, further shifts to cars, and so on. Likewise for an associated phenomenon regarding neighborhood stores and shopping centers. The "voluntary" shift to cars by some results in a necessary shift to cars for the rest.

3. Most importantly, the dynamic interplay between the benefits and disbenefits of the car, as perceived by the prospective owner, is governed by the "Tragedy of the Commons." This venerable but powerful idea was popularized by Garrett Hardin in the journal *Science* in 1968. The thesis is that individuals acting in their own interest will inevitably destroy a shared resource. Hardin's example is a common pasture. Each farmer reasons that by adding a cow he will get all of the benefit, while the damage to the pasture will be spread over all farmers. Each acts alone, leading to a competitive increase of cows, overgrazing, and ruination. The most important point is that the farmers, if they are competitive, and if they act individually, are locked into this progression: hence the "tragedy" in the literary sense. Further, an appeal to voluntary limitation must fail, since the presence of only two competitive individuals among a crowd of people of conscience leads to the same conclusion The only solution seen by Hardin is "*mutual* coercion *mutually* agreed upon." (My emphasis.)

WHY WE BOUGHT A CAR IN TRONDHEIM

There we were in Trondheim without a car. Here's what went through our minds:

1. In Norway you stand almost as good a chance of getting killed by a motor vehicle if you don't have one as if you do, In 1976, 42 percent of the 462 motor vehicle related deaths were pedestrians, cyclists, sledders, and skiers, with another 10 percent on motorcycles and mopeds. (In the U.S. this is about 21 percent.) This high fraction is a result of the auto's rapid introduction in Norway, but in any case it's a fact.

2. The other disbenefits of cars—pollution, congestion, noise—are suffered as much by people out of cars as in. Atmospheric lead is

highest in the central city, where almost everyone shops and many work. Likewise for hydrocarbons and dirt. This is especially true since Trondheim, founded 1000 years ago, has rather narrow streets. In fact, cyclists and pedestrians experience these insults more, since they move more slowly along the same corridors; there are no separated bikepaths or walkways. We were especially exasperated to sit in a bus stuck in a traffic jam caused primarily by cars; there are no special bus lanes, as are now in use in Washington, D.C., for example.

If you buy a car in Trondheim, you add one to a present auto population of 34,000, a drop in the bucket. But on the benefit side, you have made your own life much cleaner and no less safe, while receiving all the mobility that the car represents.

We knew the environmental rhetoric, we had read the paper about the kids and senior citizens getting run down when the exceptionally heavy snows had forced them to walk on the roads. Yet after six months of walking and biking on icy streets through a tunnel of pollution with fenders brushing past our legs, of standing at bus stops breathing death, we bought a car. A rational decision.

Most of what I'm talking about is the problem of cars in cities. (Trondheim's population is 130 thousand.) You might well reason that a sane policy is to use the car for trips to the country but not in the city, or at least not when the other modes of travel are relatively pleasant—an evening trip to a movie, for example. Now comes the lesson in freshman economics. Public transport is cheaper than the car (for an individual) if you don't already have a car, but not if you do. As soon as you buy the thing, the marginal cost of driving it is less than that of the bus. We bought a ten-year old Ford Taunus (a middle-aged car by local standards). Depreciation, registration, insurance, and maintenance ran around $800 a year, but the marginal cost of running it instead of letting it collect snow was only about 8 cents a mile, mostly for fuel. As we saw it then, a five-mile round trip downtown cost 40 cents. On the bus, it cost 90 cents a head. And the bus fare was hiked 20% during our stay.

The relatively low cost of fuel, compared with the purchase of a car and with public transportation, gives a strong economic impetus to go by car always once the car is bought. The situation is similar in the U.S., where the costs of cars, fuel, and public transportation (when it exists) are roughly in the same proportion, about half of those in Trondheim. A radical change in relative prices would have dramatic effects on usage patterns. Suppose, for example, that every citizen were given a car on his 18th birthday but that fuel cost $3.00 a gallon. . . .

One month after we bought our car, we went downtown to see "Jaws," with Norweigian subtitles. It was the first day of spring in Trondheim. Cumulus streamed over the near mountains, which dazzled under 2 meters of snow. The streets were golden in the slanting light. (The sun was ours for the next six months.) The ice was gone, the wind was warm.

We drove.

DRØMMEDAL, WHICH HAS NO ROAD OUT

Later we journeyed to the fjord country to work on a farm in a valley accessible only by a two-hour ferry ride. Drømmedal, we called it, the dream valley, an absolute of awesome physical beauty, the stuff of calendar photos, a thin lush edge of dairy farms between turquoise water and 1700 meters of black granite and dazzling ice. By day we pitched hay amid the sounds of falling water. At night we rode in the tractor bucket to visit neighbors. We talked about the tunnel soon to be blasted four kilometers through Norwegian rock to allow easy auto access to Drømmedal. (The ferry now does carry motor vehicles.)

In spite of our blistered hands we were tourists. We remarked on the quietness of the place, and then realized we meant freedom from the sounds of motor traffic. After leaving the ferry we had sat on the veranda of the victorian Drømmedal Hotel. The valley's main road was in front of us, between the hotel and the fjord. In a half-hour we had seen two bicycles and not a car. And later, walking the seven kilometers from the farm to the ferry, we would be passed by three cars and a school bus. This is magical, tranquil place. Why bring in the car en masse? The replies came in language that we couldn't completely understand, but the gist was this:

The tunnel is for the children. The winters, which tourists don't see, are dark and hard. Snow depth can reach two meters, and the cows are confined to the barn from early November until the first of June. Even with subsidies, farmers don't make much. Most kids want other work. There are few such jobs in Drømmedal, but they exist in Domfjord and Spistad, which are 20 to 30 kilometers away. The valley's population had dropped significantly since 1960. To attend gymnasium or vocational school beyond seventh grade, students must go to Domfjord and return home only on weekends. And for the sons who want to remain and farm . . . where will they find wives? (The family's oldest son has a girl from Bergen, where he worked for a year.)

But, we asked, the commuting life?

Yes, perhaps that's bad, but the road will also provide jobs here. What's wrong with the ferry?

Too infrequent (three per day). Takes too long. And too expensive (almost two dollars per person each way; more for cars).

By the time the road reaches the farm it is a dirt track. Each afternoon two busloads of tourists go by, from the ferry to the icefall-overlook. In two hours they return. A few hikers bring their cars to park at the head of the train that climbs 1,000 meters to the glacier, but most are on foot, lugging their packs for fun while we toss the hay. At night the road is unlit, unused. The north star is almost directly overhead.

Would you like the road to be paved? A larger, paved parking area for the trail? At the overlook? How much traffic before your cows are hit? Your dog? Your kids?

It can never grow that much.

The conversation swung back and forth . . . access to Drømmedal for tourists with money, or escape from Drømmedal for natives. We pressed the point. It's not the problem of access, but of access by cars: their need for space, the clutter, the pollution, the noise. How much will the tunnel cost?

60 million kroner.

Suppose the 60 million were invested and the 3.6 million interest per year used to finance, for example, a fast passenger-only catamaran of the type now used in Bergen, Trondheim, Stavanger. A trip to Domfjord would take less than an hour. The fare could be subsidized for Drømmedal residents.

Not the same. It would still take at least half a day to get out. The tunnel is faster, and it would make economic sense to have a car if you could drive the whole way, from the door. It doesn't make sense if it can only be driven seven kilometers to the ferry.

We asked a last question. With the tunnel, traffic will skyrocket. Imagine your road, which passes ten meters from your house, with ten times as much traffic as now. 100 times. What is the maximum tolerable number of cars here?

Many more than we have now. But it can't grow that much.

We tried to portray Yosemite Valley, the approach to Gatlinburg, Tennessee, the parking lot at Old Faithful—and what had transpired at these places in the space of 25 years. Exponential growth, cars begetting asphalt begetting more cars. A force as strong as gravity, as natural as falling water. Lost in translation.

Soon we left, the yellowing hesjers neat in rows on the cropped green fields. It was August, and the shadows were lengthening. Already the farm was getting only six hours of sun. At Domfjord, two hours by ferry from Drømmedal, was our car.

TRONDHEIM'S FIRST SHOPPING CENTER

Back in Trondheim, we began to feel the interaction of the car and the structure of neighborhoods. We read the 2-column public service ads which said "Shop at your local store so it's there when you need it—they are closing at the rate on one every day. Contact with your local merchant means a lot." (We agreed; we like chewing the fat with Asbjørn Strømmen, who followed my wife's pregnancy and knew when our daughter was born.) In the same paper we also read 3-page 3-color ads from Obs! (the exclamation point is a part of the name), advertising its 600-car parking lot. When it was time to do some American-style heavy shopping (which contrasts with the traditional one-bag-daily routine), we vowed to avoid Obs! and motored downtown, a trip we had previously made with bus ticket and rucksack. We were bouncing two shopping carts over the quaint, tradition-rich cobbled alleys of Old Trondheim. The car was parked on the street ¼ mile away, at a meter. Attrition was high: flour-sacks, cheese, margarine were flying, smashing on the cobbles. Then we had to push the carts back, among stores. Apparently Trondheim was unsuitable for anything but one shopping bag-at-a-time.

So we tried Obs! Obs! is a step towards America: located 1½ miles from the centrum, in a muddy or snowy field, next to a ferrosilicate smelter. 60,000 square feet, with prices averaging 5% less than competition, fruit wrapped in plastic and no fresh fish. "Cheaper to live" says the sign over the air curtain. Friends who swear by Obs! told us "We like the local store where we get meat and fish (all fish at Obs! is frozen) but we can't afford not to go to Obs! for staples." And finally: "The car cost us a lot and at Obs! you can economize to compensate." Obs! even sells gasoline below competition. . . .

The people at Obs!, most of them young families with their first car, are at the margin, living on tight budgets. The car makes it possible to go to Obs!, the car (once purchased) requires it. Meanwhile Fru Andersen, a widow, who has never had a car, makes her daily trip to her local market. And we, after our one trip to Obs!, went back to Asbjørn Strømmen. But we kept the car.

BACK IN THE U.S.A.

Norway allowed us to go back in auto history a quarter-century and to feel the force of rapid change. On returning to Champaign-Urbana, Illinois, we expected that feeling to be absent: "it's already happened." To a large extent this is true, but we were surprised to again sense the dynamics. In two years a new enclosed shopping mall had sprouted on 40 acres of excellent agricultural land 1½ miles north of Champaign, in one stroke annihilating all the downtown stores. To its credit the mall can be reached by bus, but since 30 of the 40 acres are asphalt parking lot, it is clear what's intended. (Ironically, the Champaign merchants had only shortly before converted the main drag to a pedestrian mall.) A child had been killed by a car 150 yards from our door while we were gone. At our corner in the last 2½ months there have been two minor wrap-ups and one acceptable atrocity when an acceptably drunk high schooler crashed the football field fence and laid a ribbon of tire tracks from goal post to goal post, and escaped. Buick is advertising "Life is to enjoy" and the C–U bus system, not a bad one, just raised its fare from 25¢ to 30¢ while the gasoline price has dropped several cents per gallon (about 64¢ now). A street which had been closed to traffic adjacent to the University of Illinois was reopened when local merchants feared a loss of business. In this Midwest college city of 130 thousand (including 30 thousand students) there are 250 thousand person trips/day by car. Bus use (6 thousand person-trips/day) is actually increasing, but the big issue is whether to build an additional interchange on Interstate 57 (I57, 72, and 74 intersect within 2 miles of town). Carter's gasoline tax was killed. Denver offers free off-peak bus service, which doesn't help the commuting problem. (With today's affluence and gasoline price, even free mass transit is apparently too expensive!) I'm more sensitive to these changes now.

SINCE WE LEFT, NORWAY IS GETTING ITS OWN AUTO LOBBY

Because cars are not manufactured in Norway, there is much less chance that if you resist the car it will cost your neighbor his job. This fall, however, the Norwegian government has made a deal with Volvo of Sweden to start producing Volvos in Norway—the first attempt at motor vehicle manufacture in Norway (population 4 million) since the short-lived Trollmobile 22 years ago. Soon three to five thousand Norwegian jobs will be directly dependent on car manufacture. One more piece in the dynamics, one more element of instability.

In spite of my admonition to myself, I have given a number of anecdotes. What all this leads me to is that to expect or encourage individual action to limit the car is useless, and that the collective measures which are required must be strong. I was frankly surprised to see that Norway, in spite of an advanced social environmental consciousness and a history of collective action, simply is underestimating the forces and, especially, the mechanisms involved. In the U.S., because the automobile is so entrenched, whatever is going to work must come slowly to avoid disrupting jobs, communities. In the end, though, I am still at a loss. The hypothetical person I mentioned at the beginning of the article, who would admit that continued growth of cars is bad for America, will probably conclude that because the car requires a collective solution it is irrestible. The collective consciousness doesn't exist here.

All I can really conclude is that efforts should be aimed at broad, non-voluntary programs: gas taxes, weight taxes, fully busting the Highway Trust Fund, tough drinking/driving laws, higher costs for parking, and especially, that these measures are felt uniformly, equitably across economic classes. It has been said that addiction and envy are the dual pitfalls of a consumer society. For the car, I accept the desire for addiction as unchangeable. Managing envy (or competition), as it drives us through the Tragedy of the Commons, is where we have a chance.

THE "SOFT ENERGY PATH"—I

(By Amory B. Lovins)

This third selection by Lovins (the other two are included in the section on General Energy Policy) presents more recent calculations on the progress in what he defines as "soft" technologies, as well as his estimates as to their present and potential costs.

SOFT ENERGY TECHNOLOGIES [1]

(By Amory B. Lovins)

INTRODUCTION

The energy problem is traditionally considered to be how to expand readily available (e.g. domestic) energy supplies to meet extrapolated homogeneous demands. A tacit identification of the rate of growth of primary energy use with the level of well-being leads to subsidization of energy supply, lest price elasticity of demand stall supposedly essential energy growth. Aggregation of thermodynamic categories of demand leads to the almost universal supply of premium forms of energy—fluids and electricity—as a highest common denominator. Belief in economies of scale leads to ever larger and more centralized facilities. Faith in the ability of technological advance to overcome resource depletion only accelerates both, within a time horizon shrunk by high discount rates. Such an energy future, in short, is merely the past writ large. While numerical estimates of its details are diverse and in rapid flux—generally toward lower projections—the qualitative shape of its major terms for the United States resembles Figure 1 (1, 2).

The rising economic, environmental, and political costs, hence the dwindling practicality, of this "hard" energy path (1) are increasingly troublesome even to those who accept its premises. Some students of energy policy, believing these marginal costs to be prohibitive, have suggested (1, 2) that the energy system should evolve differently, according to a redefinition of the energy problem: namely, how to meet heterogeneous end-use needs with an elegant frugality of energy, and other resources, supplied in the most appropriate way for each task. This emphasis on the tasks we are attempting with the energy and the

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Review completed May 26, 1978.

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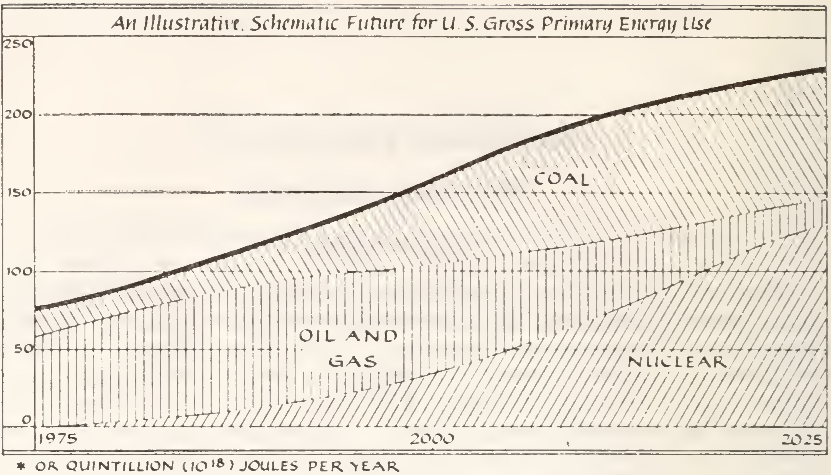

FIGURE 1.—An illustrative hard energy path for the United States. Figures 1–5 are reproduced, by permission, from Lovins, A. B. 1977 *Soft Energy Paths: Toward a Durable Peace.* Cambridge, Mass: Ballinger and Friends of the Earth.

best way to do each task leads to a different view of the kinds of energy supply we need from now on. Our energy supply problem becomes essentially one of heat and portable liquid fuels. More electricity, particularly from centralized sources, becomes an irrational response to that problem. Comparisons between different kinds of big power stations (3) accordingly become irrelevant, since the heat and liquid fuel needs can be met more cheaply, quickly, surely, and easily with appropriate renewable sources that are already available, than with "hard technologies" such as synthetic fuel and central electric plants.

The resulting "soft" path, which for the United States might resemble Figure 2 (1), combines greatly increased efficiency in using energy, including transitional fossil fuels, with the rapid introduction of "soft technologies." These, the subject of this paper, are defined (1, 2) as diverse renewable sources that are relatively simple from the user's point of view (though often technically very sophisticated [2]) and that are matched in scale and in energy quality to our range of end-use needs. Craig et al (4) have also suggested further criteria—soft technologies are environmentally benign, subject to "graceful failure," foolproof (or resilient), and flexible—but these descriptions, though accurate, are probably derivative rather than essential to the definition.

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[2] My pocket calculator offers an analogy: though I could not build one and do not understand its operation detail, its functional simplicity lets me integrate it into my life as a tool rather than a machine; I run it, it doesn't run me. Yet it uses very high technologies.

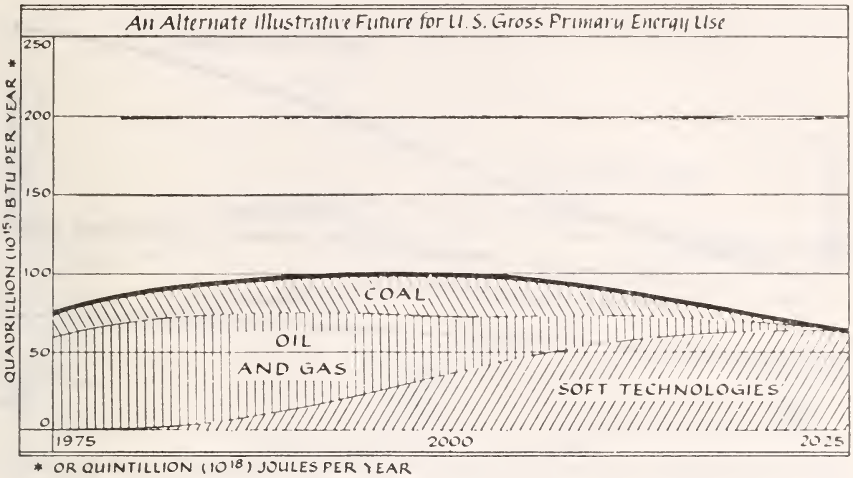

FIGURE 2.—An illustrative soft energy path for the United States.

Though the hard and soft energy paths typically contrast high and rising energy use with low and falling energy use, respectively, neither the rate of energy conversion nor its time derivative is a defining feature. Indeed, as Figures 3 and 4 illustrate schematically, most of the difference in primary energy between typical hard and soft paths arises from the dominance, in the hard path, of energy distribution and conversion losses. In the soft path, these losses are virtually eliminated by matching energy supply in scale and in energy quality to end-use needs. Meanwhile, much greater emphasis on end-use efficiency—which increases three to fourfold through purely technical improvements over 50 years in the soft path, compared with a factor of less than two in the more supply oriented hard path—leads to greater total "functions performed" (goods and services forming a surrogate for GNP) in the soft than in the hard path.

Nor are these two paths distinguished only by choices of hardware—by whether they increase reliance on hard or on soft technologies—but also, importantly, by the sociopolitical structure of the energy system. The hard path is one whose polity is dominated by such structural problems as centrism, autarchy, vulnerability, and technocracy (1, 2). The soft path has an antithetical [3] and more tractable set of political problems, chiefly those of maturely exercising pluralistic choice. Using hard technologies entails hard path political problems; using soft technologies permits, but does not ensure, avoidance of those problems—solar collectors could in principle be deployed by central coercion—and is thus a necessary but not a sufficient condition for a soft path.

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[3] Since the political conditions defining the two paths cannot logically coexist, it is a category mistake to speak of a hybrid hard-and-soft path (5).

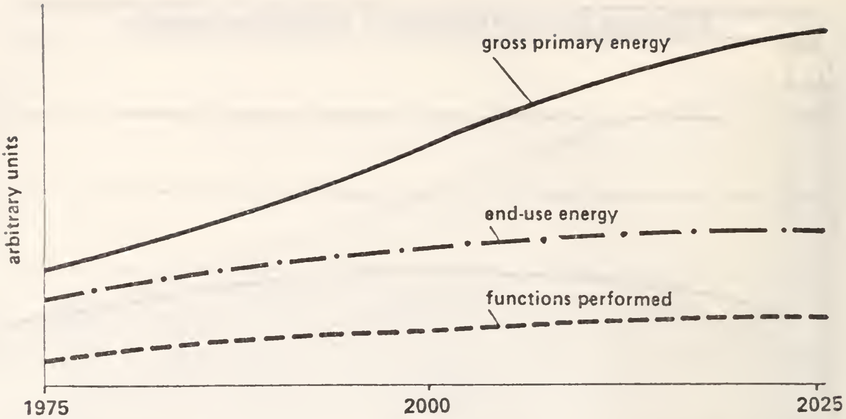

Figure 3.—Primary and end-use energy and functions performed in an illustrative US hard energy path.

Moreover, the argument (1, 2, 5) that the two paths are mutually exclusive does not rest on any notion that soft and hard technologies are technically incompatible, for they are not: indeed, in a soft path (Figure 2) they would coexist for 50 years as their proportions changed from nearly all hard to nearly all soft. The exclusivity argument concerns not technologies but paths—broad patterns of internally consistent evolution of the energy system within its full social and political context. The two paths are culturally incompatible (each entailing an evolution of perceptions that makes the other kind of world harder to imagine), institutionally antagonistic (each requiring organizations and policy actions that inhibit the other), and logistically competitive (each requiring money, materials, fuels, work, skills, political attention, and time whose commitment forecloses the other path). Where we are now illustrates this burgeoning exclusivity: just the past few decades' pattern of commitments has already given us many analysts who cannot imagine any other approach to the energy problem, many rigid institutions like the utility sector that are manifestly resisting public pressures (e.g. for environmental and rate reform), monolithic constituencies with the power to reinforce past commitments, and an unduly restricted range of near-term technical options. And some commitments narrow future choice through their physical irreversibility.

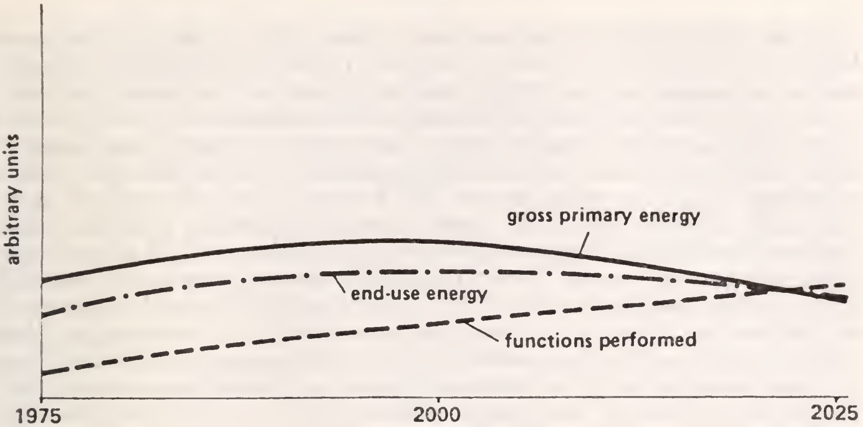

FIGURE 4.—Primary and end-use energy and functions performed in an illustrative US soft energy path

The longer the time scale we use for decisions about the shape of the energy system, the less important economic criteria become compared to environmental and social ones (4, 6)—whether or not one believes in high discount rates. Indeed, environmental and social criteria may already be more important in most major political decisions about energy than the narrow rationale of private internal cost: most such decisions seemed to be based on political expedience and later justified by adjusting subsidies. Even today, the costs and performance of energy systems of all kinds are not known as precisely or confidently as we would like, and technical uncertainties plus rapid technological change make the cost uncertainties of most long-term supply options overlap in each end-use category within a range of perhaps half an order of magnitude. Nevertheless, because some analysts consider small present differences in private internal cost to be important, this paper compares the costs (as well as the deployment rates, risks, and sociopolitical and geopolitical effects) of soft and hard technologies. It also summarizes one view of the technical state of the art of soft technologies themselves. Other crucial ingredients of a soft path—such as greatly improved end-use efficiency, transitional fossil fuel technologies, and policy instruments for implementation—have been surveyed elsewhere (2, 5).

END-USE STRUCTURE

Since energy is but a means to human or social ends, and is useful only insofar as it performs specific tasks relevant to those ends, anyone seeking to perform tasks with the least possible energy and trouble should start with an inventory of tasks. To design a rational energy system, we need to know the type, quality, unit scale, and degree of geographical clustering of energy needs as a function of space and time. Such an elementary data base does not exist anywhere. Early efforts to derive a thermodynamic structure of end use (2) have been obliged, by a paucity of data, to aggregate many end-use categories and all regions within particular countries at fixed dates. Yet the results are instructive.

In the United States, for example, about 58% of all delivered enthalpy—the quantity of energy without regard to its quality—turns out to be needed in the form of heat, and most of that is at low temperatures: a total of about 35% below 100°C and a total of 44% below about 315°C, which is easily within the range of present nontracking solar collectors (7). A further 34% is needed as fluid fuels for transportation (31% for vehicles and 3% for pipelines). A total of only 8%—half of it for industrial electric motors—is for the premium uses that require the high quality of electricity and can use it to advantage, thus giving us our money's worth from this special, very costly form of energy (often costing (8) over $100 [4] per enthalpic oil-barrel-equivalent at the margin). These premium uses include lighting, electronics, telecommunications, electrometallurgy, electrochemistry, arc-welding, electric motors in industry, in home appliances, and in railways—in short, all present electrical uses except heating and cooling. But this 8% figure implies that present US electrical supply is 1.6 times the present appropriately electrical needs—roughly 2.6 times if straightforward technical fixes (9, 10) were used to increase end-use efficiency. The United States could in the latter case supply all its appropriately electrical needs with existing hydroelectric capacity, readily available microhydroelectric capacity not requiring new dams, and a modest amount of wind-electric capacity, and therefore with no central power stations, no changes in life-styles, and large savings in capital and fuel. (Power stations now burn nearly 30% of US fossil fuel, and this is proposed, as Figure 3 sketches, to increase steeply.) This thought experiment suggests how far out of step we are with supplying energy only in the quality needed for the task at hand. The disproportionate economic and social costs (see below) of any form of central electrification at the margin offer a strong incentive to supply electricity only where it is really needed.

Though rough projections suggest that the electrical share of total end-use energy needs, if not the absolute amount of electricity, might increase because efficiency improves faster in using heat and liquid fuels than in using electricity, more sophisticated analysis might not confirm this (11). Detailed studies of appliances and motors (12–15) and more general considerations of industrial process design, and the selection, use, and recycling of materials (16–24) suggest that the scope for improving Second Law system efficiency (20) might not be much less for electricity than for other energy forms (11).

International comparisons (11) are sparse but suggestive. The heavily industrialized Federal Republic of Germany (FRG), owing largely to its more efficient vehicles and industrial processes, has an end-use structure even more heavily biased toward low-grade heat than the United States: roughly 75% heat (of which a total of 50% is below 100°C) and a total of 63% is below about 315°C), 18% liquids for vehicles, and 7% appropriately electrical (2). The Swedish end-use structure is nearly identical (T. Johansson, personal communication, 1977), and Canada, Britain, France, and every other country studied all show the same saturation of electrical needs (11). Developing countries, even those with mild climates, probably have today an even greater bias toward heat at modest temperatures, e.g.

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[4] This corresponds to a delivered electricity price of about 63 m$/kW(e)-hr. All prices and costs in this paper (save as noted) are in constant 1976 US dollars, and, if not quantified, refer to real (constant-dollar), not current-dollar, values.

for cooking, and an even smaller relative need for high-grade energy (25) than, say, the FRG.

As noted earlier, the spectra of unit scales and densities of end use are important but poorly known. (Even less well known are correlations between the thermodynamic and the scale structure of end use, needed for designing total-energy systems that cascade successively lower temperatures of waste heat.) Estimates of the order of magnitude are nonetheless helpful. The heating load of houses is typically measured in 10^3 W; the energy needs of large industrial facilities range from pathological maxima of the order of 10^9 W to normal maxima of the order of 10^8 W. Most end-use devices used in production are clustered in factories or offices needing less than about 10^6 W. Most end-use devices important to our daily lives need of the order of 10^1–10^3 W and are clustered in living or working units requiring of the order of 10^3–10^5 W. Most production processes of practical interest have long been carried out in units of the order of 10^5 W or less. Thus it is not obvious *prima facie* that energy must be converted in blocks of the order of 10^9–10^{10} W as in modern refineries, power stations, and proposed synfuel plants. The next section of this paper treats some emerging arguments (2, 11), chiefly economic, for not perpetuating such a mismatch of scale between souces and needs.

SCALE ISSUES

Doctrinaire belief in economies of scale has long dominated energy decisions. It made the capacity of the largest turbogenerator double "every 6.5 years through five orders of magnitude" (26), increasing centralization because total grid capacity doubled slightly more slowly. Yet with changing circumstances and wider system boundaries, "many of the advantages claimed for large scale may be doubtful, illusory, tautological, or outweighed by less tangible and less quantifiable but perhaps more important disadvantages and diseconomies." (2) Thermal power stations, though not a soft technology, illustrate eight classes of effects that enhance the economic and technical attractiveness of appropriately scaled technologies, both hard and soft. No theory is available for optimizing unit scale with respect to all these effects (let alone others, notably political and psychological effects (2), that become important if the system boundary is drawn more widely).

Construction

Direct construction costs—those for materials and field labor—often follow a classical two-thirds-power scaling "law." These economies of large scale are not only counterbalanced in many cases by poorer performance or high indirect costs (see below), but also forego the potential advantages of mass production. If power stations were not too big to mass-produce like cars, their unit power cost could probably be reduced by an order of magnitude. (Cars cost of the order of $40 per kW of crankshaft power, and their prime mover could be made long-lived at similar cost if bodywork and gadgets were omitted.)

Operation

Central delivery of fuel and the ability to convert a single central unit to substitute fuels, can save money, but both are irrelevant to solar technologies for which distribution of the energy flux as free and (stochastically) assured. Centralized technologies can attract and support the specialized maintenance cadres they require, but at the cost of increased vulnerability to those cadres' whims (as in British electricity strikes). Dispersed technologies seldom require such high maintenance skills or standards, since they are simpler, more comprehensible, and likely to "fail gracefully" (4) with minimal consequences. On the contrary, the greater complexity of centralized, high-technology plants is likely to multiply failure modes, lenghten downtime, make repairs harder, increase equipment and training cost for maintenance, and increase carrying charges on costly spare parts made in small production runs. There also does not appear to be evidence for greater technical efficiency in larger units, particularly within the solar technologies (27); and for each example of a bigger power station with slightly better steam conditions, one can cite a stronger counterexample of a smaller combined-cycle or combined-heat-and-power station with far greater system efficiency. Indeed, easier integration into total-energy systems and combined food-and-energy systems is among the greatest economic attractions of tractable scale.

Distribution

Centralized energy sources are mismatched (2) to an end-use power density which, for 1965–71 US electricity, is (28) of the order of 30 mW/m^2 of land area (ranging an order of magnitude either way among US private utilities). The density for nonindustrial users is only half as great, or 1/12,000 that of sunlight, which implies an average service radius of the order of 150 km per 1-GW(e) plant. (the actual average haul length at the margin is about 350 km in the United States, and 100 km in Europe, partly to benefit from load diversity.) This mismatch between supply and load density entails a costly transmission and distribution network that accounted for about 70% of the 1972 cost of delivered electricity to nonindustrial customers of US private utilities (28), which was over twice the cost of generation! (The corresponding 1977 ratio for natural gas was also about 70:30.) This is undeniably a diseconomy of centralization, as are the pervasive energy losses in transmission and distribution. Both costs and losses-important also in nonelectrical systems (2)—could be greatly reduced by better matching of scale to end uses.

Availability

Larger unit scale in components (29, 30) or in power stations (31–34) tends to decrease reliability and so increase both heat rates (32, 34) and energy costs. Decreased reliability can be due to outrunning engineering experience by scaling up too quickly, failure to improve quality control in proportion to the quantity of components that can fail (32), or fundamental problems of complexity and operating requirements (e.g., larger turbines have larger stress at the blade root, which encourages the use of exotic materials that are more likely to have unexpected properties and to show diminishing returns in proportion to cost and talent invested: any technology with such a sustained short scale-doubling time is bound to come unstuck eventually) Figure 5 (2, 34) shows a striking example: in a nearly even-aged sample comprising half the thermal stations commissioned in the United States during 1972–4, as unit size increased 20-fold, average unavailability quadrupled. Far larger samples show similar effects (33), with size correlations much stronger than age correlations

Reserve Margin

Unavailability is a particularly grievous fault in large units because large and costly increments of backup capacity are needed to prevent grid failure. Recent studies (35, 36) of typical interconnected grids suggest that building several smaller units, say of 300–400 MW(e) each, instead of a 1000-MW(e) plant, would provide the same level and reliability of service with about a third less new capacity—simply because the more numerous smaller plants would be extremely unlikely to fail all at the same time and hence would require less reserve margin. If this is correct, then 1 GW(e) of nuclear capacity at the margin should be compared in costs and impacts with perhaps 0.7 GW(e) of coal-fired capacity because the latter is available in smaller units (37). For still smaller units, such as ~10-MW(e) fuel cells sited at distribution substations, the marginal capacity savings to do the same job may exceed 60% (38), since such dispersion not only saves reserve margin but also protects users from failures in transmission between them and a remote station, which is the dominant cause of supply failures. [One estimate ascribes only 5% of US supply failures to a failure in generation (39).]

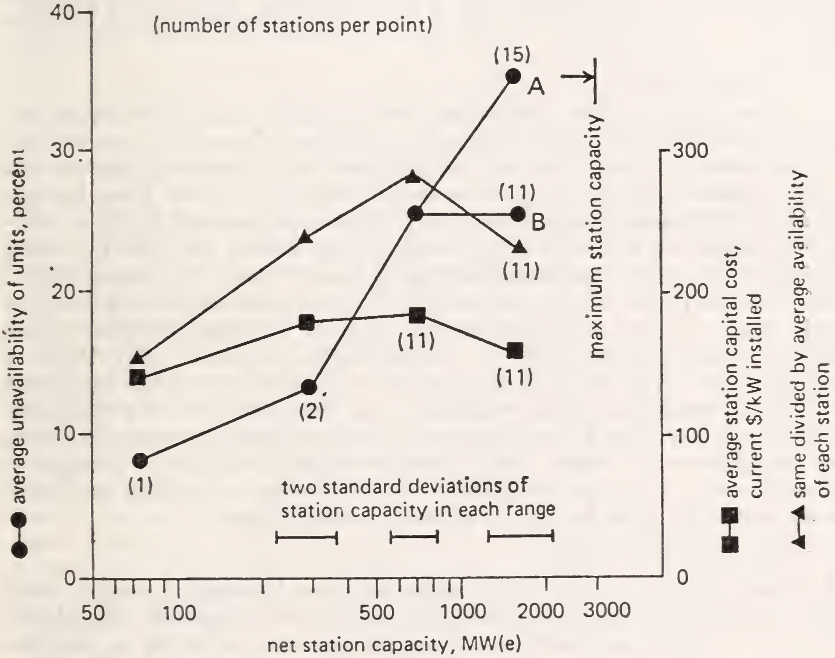

Figure 5.—Average unavailability and capital cost vs unit size for 29 US thermal power stations commissioned in a 2-year period during 1972–4, plotted from tabular data in (34, see also 2, p. 92). The sample includes half the US thermal power stations commissioned during the period, represents every region except New England, and includes 17–18 coal-fired, 2–4 nuclear, 3 gas-fired, 2 gas- or oil-fired, and 1–2 oil-fired stations.

Point *B* on the graph is from the tabular data; point *A* is from the graph (34, p. 51), and presumably reflects high unavailability in the four very large stations whose unavailabilities are not shown in the tables. Elsewhere the tables and graph in (34) are consistent. The lower point (B) is assumed in this graph for calculating the right-hand triangular point.

Lead times and indirect costs

Cost escalation and cost of money show no economies of scale. As these terms become larger components of total cost, due to the interrelated increase of capital intensity, scale, technical complexity, perceived impacts, and lead times, total economies of scale decline (40). There is some evidence that for a sufficiently wide range of unit sizes, economies of scale in capital cost per kW actually become negative, as shown in Figure 5 (2, 34), where capital cost per kW(e) installed is less for a small station than for a very large one. This may be because larger stations are so much slower to build that they are far more exposed to (*a*) costs escalation, (*b*) interest during construction (40), (*c*) higher cost of money due to lower self-financing ratio and the frequent need to finance an unfavorable cash flow with short-term paper (41), (*d*) premature completion (a major risk when demand is uncertain (42)), (*e*) changes in regulatory requirements during construction (43), (*f*) union wage pressures, and (*g*) high transaction costs of siting.[5] While recent cost analysis (44) of 39 US nuclear power stations shows a modestly significant net economy of scale—each 100 MW(e) increase in unit capactiy decreases construction costs $22 per installed kW(e)—the plants are all in the size range shown on the right hand side of Figure 5, which is thus not inconsistent with this finding.

Control of residuals

It is often claimed that centralization simplifies control of emissions and other side effects. This argument is neither absurd nor conclusive. Smaller scale often reduces residuals by permitting more efficient total-energy systems, and permits more flexible and inherently more benign processes. [Fluidized-bed combustion is now commercial (2, 5) at 10^7–10^8 W(t) but not at 10^9 W(t)]. Smaller scale lowers the risk and cost of failures in pollution-abatement equipment (there is a strong fiscal incentive to bypass a defective scrubber rather than shut down a major power station). And smaller scale guarantees, by siting the plant near its users, that they will insist it run cleanly and quietly (45). When a large plant is rurally located the agrarian politicians are often impotent to enforce environmental standards in the face of overwhelming economic power. Small plants automatically allocate operational costs and benefits to the same people, rather than to different groups at opposite ends of the transmission line, thus decreasing the potential for inequities in distribution of environmental costs.

Other issues related to scale

Interconnection of multiple major sources through a supply grid can save capacity by load diversity, and can reduce the likelihood (though perhaps increase the consequences) of catastrophic failure. Interconnecting smaller, more dispersed sources through the same grid keeps these advantages while adding the option of not being dragged down by a failing grid, and thus increases resilience (46).

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[5] H. R. Holt points out that if difficulties in siting and licensing lead utilities to maximize installed capacity per transaction, the plant may then be so big and problematical that transaction costs for siting the next plant increase, and so on exponentially.

Large scale plants may make it easier to use and finance the best technologies currently available, but smaller scale with shorter lead times may, at each stage during rapid technological evolution, sink less capital in inflexible plants and infrastructure. Large scale plants pack more capacity onto a site that is increasingly hard to find, but smaller scale, as European district-heating experience shows, can reduce local environmental and social impacts enough (especially by using existing sites of old municipal power stations) that siting becomes relatively easy (45). Energy supply by a centralized entity such as a utility grid may increase convenience to users who do not care to become involved except by paying the bill, but may cause others to feel a humiliating and even alienating dependence on remote technical bureaucrats who tell them how much energy they can have at what price, and can disconnect them if they argue. Large unit scale increases incentives for and social vulnerability to sabotage and disruption, including war, so reducing national security. Large scale makes truly large mistakes more likely by reducing diversity, (46) encourages oligopoly and technical monopoly among suppliers, is less relevant to the needs of developing countries (25), and tends to concentrate political and economic power. Further, large scale plants submerge personal responsibility in large, anonymous technical organizations where it may slip through the cracks altogether. Large scale gives those organizations disproportionate and self-reinforcing policy influence because of the money and talent devoted to them. From the technologists' point of view, big technology is less fun to do and too big to play with, so discouraging fundamental innovation. The converse is emerging as one of the most important features of soft technologies: one person can understand them and make basic conbtriutions to them, for there is, as far as we know, nothing in the universe quite so powerful as four billion minds wrapping around a problem. For this reason, many of the most exciting solar developments are the work of individuals, often with no technical support and with no information links to government-sponsored "big science."

These and similar diseconomies of large scale suggest qualitatively, with some quantitative support, that the case for building highly centralized energy systems has been much exaggerated and may even (2) be generally invalid at the margin. Of course there are some applications where large scale may make sense. If a big smelter is such an example, it would be just as silly to run it with little wind machines as to heat houses with a fast breeder (47). Yet the big systems needed for such special uses are already in place and can be used to advantage without multiplying them further. The question of appropriate marginal scale remains fruitful ground for public policy debate, and the stakes—the costs, including social costs, and the losses of energy distribution—are high and rapidly increasing.

TECHNICAL STATUS

The foregoing considerations suggest that diverse, end-use-matched, comprehensible, renewable energy technologies, each doing what it does best, and none trying to be a panacea, can contribute substantially to meeting our range of end-use needs, if physically available at reasonable cost. But are they?

Few soft technologies are new in principle: Solar reflectors and passive solar architecture are millenia old, flat-plate collectors and heliostats over 200 years old, and photovoltaics and solar heat engines over 100 years old. Thirty percent of the houses in Pasadena used solar water heaters in 1897. Fuel alcohols (from wood and crop wastes) blended in 4 million cars supplied 18% of Europe's motor fuel in 1937. Denmark had of order 100,000 wind machines in 1900 supplying ~200 MW of shaft power, while the United States today uses over 150,000 small wind machines and has used over 6 million. Yet since the end of the era of cheap oil and gas came into sight, a recent burst of engineering development, much of it nongovernmental, has yielded a wide range of technically modern and often greatly improved soft techonologies that are "technically mature," in the sense that they face no significant technical, economic, social, environmental, or ethical obstacles, though many still require sound product engineering. The range of options appears sufficiently rich (48) to support a contention (2) that the soft technologies already proven and already entering commercial production are enough, even in Japan or Denmark (49), to meet essentially all energy needs in 2025, without assuming any solar-electric technologies (such as photovoltaics) or technical breakthroughs. Let us now survey, briefly and far from exhaustively, some of the available types of soft technologies by end-use category.

Low temperature heat

Heat at temperature below about 100°C, the dominant term in world end-use energy needs (11), can be readily supplied by commercial solar devices now made by several hundred US manufacturers (27, 50) at a ~1977–8 rate[6] probably exceeding 4×10^5 m^2/year, demonstrated in many thousands of US houses and apartments,[7] and able to be homemade by do-it-yourselfers (51, 52). Similar devices are widely made and used outside the US—e.g. in 2 million Japanese and ~200,000 Israeli dwellings. Remaining developmental problems with active collectors are straightforward and rapidly being resolved with low technology (53). With good design and workmanship, which are far from universal, lifetimes of both air and water collectors can exceed 30 years. First Law efficiencies for flat plats at near-ambient inlet temperatures are typically of the order of 0.4–0.5 or more with air or liquid coolants. In cloudy climates, selective surfaces can be used to convert diffuse radiation to respectable temperatures. Integration with the building fabric (54), solar district heating (55, 56), and a more mature solar market with fewer middlemen should continue to cut costs. Mass production for the expected large market may help a bit too (48). Novel collector designs of currently unknown operating life are under development, ranging in installed price from a few tens of dollars per m^2 for paper-phenolic-composite honeycomb sheets

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[6] Doubling every 8 months or so; excludes a similar quantity of swimming-pool collectors.

[7] The National Solar Heating and Cooling Information Center, P.O. Box 1607, Rockville, Md. 20850, (800) 523-2929 [In Pa. (800) 462–4983] is a useful clearinghouse.

(J. Plunkett, personal communication, 1977) or English roof tiles with glazed water channels to a few dollars per m^2 for plastic-film assemblies weighing less than 1 kg/m^2 (56). Present uninstalled retail prices for many kinds of conventional preassembled flat-plate collectors are typically \$85–210/m^2 (53, 57), with some types (e.g. Calmac Sunmat®, Reynolds Torex®) substantially lower (the former is \$33–45/m^2 or \$71–80/m^2 installed (27), the latter \$112–124/m^2 installed (27)). Prices of commercially installed systems—new or, often, retrofitted—are about \$100/m^2 today for some conventional double glazed flat plates of good quality if one uses simple but effective field-erected collectors (B. Anderson, personal communication, 1977) or shops carefully for preassembled collectors in a relatively mature market such as California (27, 58, 59). This ~\$100/m^2 is ERDA's price target for 1980 and seems virtually certain to be beaten in the 1980s. With only moderately astute shopping, system prices can be nearer \$150/m^2 (27, 58). Higher prices, say around \$215/m^2, are common, especially in complex packaged designs and in calculations by and for federal agencies (60; cf 61). Still higher prices (5) are used by those who wrongly think pathological cases are representative or who are defending high markups on their own brands of solar equipment.

Some demonstrated solar heating methods require no formal collection hardware. Most important—the method of choice for any new building, since marginal capital cost is then approximately zero—is passive solar heating. This uses heat captured and stored by the building fabric, including windows and perhaps thermic-diode panels, without active circulation of a working fluid (51, 52, 58, 62, 63). Passive, completely solar space heating, with storage in a convective rock bed, water, or building mass, is possible with meticulous attention to heat-conserving building design, even in severe climates. Proprietary research has, for example, reportedly produced 18 completely passively heated buildings now operating in the Albany area (43°N. latitude, 28 percent sunshine, design temperature −20°C, ~3800–4300°C-day/year). Such architects as Lee Porter Butler and David Wright have shown that passive 100 percent solar space heating, even in such severe climates as Wyoming, can reduce total house capital costs to \$250–310/m^2 floor (1977 contractor prices) (D. Aitken, personal communication, 1978).

Many hybrid designs, almost passive but with modest forced circulation of air or water, are also proving successful, particularly those using greenhouses (51) and solar-boosted heat pumps. Ingenious passive control devices are available. Solar ponds, orginally developed in Israel (64), are the subject of recent breakthroughs there (A. Kalisky, personal communication, 1978); temperatures over 100°C have been achieved and there are several impressive demonstration projects. Solar ponds can also perform remarkably well (>90°C) in temperate climates (65; W. von Arx, personal communication). Both active/passive hybrids and solar ponds may be usable for retrofits at rather low cost and are generally very much cheaper than any active flat-plate systems. With passive or active systems, simplicity works best, but is all but unheard of in official programs.

Classical calculations (66) showing that completely solar, zero-backup space- and water-heating is prohibitively costly—as Solar House I at MIT showed in 1939–41—are seriously out of date; they assume excessively costly (~\$130/m^3, riveted steel) storage tanks, pre-embargo fuel prices, and, most important, energy-inefficient buildings. Reducing the annual average heat-and-water-heating load of a house to $\lesssim$ 1 kW(t) with stringent insulation and with heat recuperators on exhaust air [8] and water—worthwhile no matter how the house is to be heated—inverts the solar design philosophy, for by reducing the total and especially the winter peak heat load, it makes heat storage cheaper than backup. (Water, rocks, and concrete for storage cost less than oil, copper, and stainless steel for backup, provided the building is heat-conserving enough for a reasonable storage volume to suffice.) Experience in Denmark, Canada, and the United States shows that in a single house, sensible-heat water storage [9] operating as a buffer between insulation and heat needs, with a time constant of the order of 2–4 weeks, can yield 100 percent solar heating with modest storage volumes—of the order of 0.4–0.5 m^3/m^2 collector in the lower 49 United States, and around 0.7 in Denmark (68, 69). With modern tank technology (70, 71) priced at 1 $\lesssim$ \$21–34/m^3 installed, for sizes of the order of 10^2–10^{1}m^3, storage accounts for only 10–^{5} of total capital cost, and heat costs with \$50–200/m^2 installed collector-system prices compete with marginal [10] sources (2, 55).

Solar heating costs appear to be generally twice as low in neighborhood-scale systems (10^1–10^3 dwelling units). This is because the large shared tank, with its better ratio of variable to fixed costs, has very low marginal cost per m^3, and, with its high volume-to-surface ratio, has very low heat losses, typically of the order of 5 percent/year. It can therefore conveniently operate on a true seasonal cycle with several m^3/m^2 collectors. Collectors can then run at full capacity all year round; collectors can be sited and often oriented without restriction and installed in bulk; tanks can be better stratified or segregated into vertical cells (56); thus collector efficiency, both thermodynamic and economic, improves and total cost decreases. For example, even assuming \$190/m^2 collector systems, \$59/m^3 storage,[11] and rather poor building thermal efficiency entailing excessive storage, neighborhood seasonal-storage systems appear competitive with 1976 (~\$8/bbl at the well-head) oil heating in Canada (55). Some analysts (T. B. Taylor, personal communication, 1977) share the author's view that such systems, properly designed, are generally cheaper than current fuels, while 100 percent solar heat for single buildings may or may not be (though it is cheaper than long-run marginal alternatives). Neighborhood-scale projects are being built or planned in Vermont, California, and West Germany. Others with seasonal storage include a shopping center in Holland, several buildings in Canada (72) including a General Motors warehouse, two projects[12] in Sweden, and reportedly several in the USSR.

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[8] AB Atomenergi (Studsvik, Sweden) and Mitsubishi Electric Company make effective, cheap air recuperators out of plastic tubing and corrugated cardboard respectively. A counterflow design by R. W. Besant et al (Department of Mechanical Engineering, University of Saskatchewan, Saskatoon) is over 90 percent efficient and permits completely solar heating with a small collector and storage in a 6000°C-day/year climate (unpublished data, 1978).

[9] Assuming a 45–50°C swing. Rock-bed storage is an attractive alternative or adjunct (51). Latent-heat storage, in experimental use (27, 70) or under development (67), is not required.

[10] OTA (27) finds 100 percent solar heat for large buildings competitive with present electric resistance heating in three of four cities studied, assuming excessive (\$80/m^3) storage cost.

[11] G. Leach has pointed out that Equation A–3 in Reference 55 should read $C_v = C_e + 2C_s(\pi h)^{1/2} + V^{-1/2} + (C_b + C_l)/h$, so Equation A–5 should read $C_v = 0.122 + 48.2V^{-1/2}$. From the data given, the calculated \$59/m^3 should be \$36/m^3, and even this is too high (70, 71), as are assumed collector costs.

Hybrid systems producing low-grade heat from cooled photovoltaic arrays and from wind-driven turbulence cells or heat pumps show promise and are becoming commercially available. Wind is especially interesting in many high-latitude sites because it tends to coincide with winter peak heating loads, complementing insolation. Geothermal district heating may be useful in many areas, though it is not included here because it is seldom renewable at reasonable rates of heat extraction. Rural wood heating is already sophisticated (73) and widespread, and is made even more attractive by densification processes for woody biomass (T. B. Reed, unpublished data, 1978). Solar cooling, typically with LiBr absorption chillers operating above 80°C, is routinely available for large buildings and works well but is expensive; clever, often traditional, building design or retrofit can generally eliminate the need for active cooling even in the tropics.

Medium- and high-temperature heat

Among the cheapest solar collectors now marketed are several tracking concentrators (27, 74), one with factory costs of \$50/m^2, and over ten others ~\$100–200/m^2. The 5800°K thermodynamic potential of direct sunlight can be used to advantage by focusing with mirrors or Fresnel lenses. The potential of diffuse light—~1340°K for isotropically scattered red photons (E. Thorndike, personal communication, 1977)—can be used by putting a highly selective surface (visible absorptance $\alpha \div$ infrared emittance $\epsilon \sim 55$–60) in a hard vacuum, yielding $\gtrsim$ 400–600+°C heat under load from a rather "weather-insensitive" device. The latter method is promising for cloudy northern climates, as highly selective multilayer thin-film coatings can probably be mass produced for a few dollars per square meter (76, 77)—since they need not be optically perfect—and evacuated tubes without them, such as the 167°C General Electric collector, should wholesale for \$48–81/m^2 (27). Such high selectivities have been attained in both reported (76, 77) and proprietary work; film stability appears adequate at $\alpha/\epsilon \sim 30$ and ~500°C (76, 77) and should be adequate at $\alpha/\epsilon \gtrsim 50$ by analogy with modern laser mirrors.

Focusing, the more conventional approach, does not necessarily require tracking the sun; a nontracking compound parabolic (Winston) collector of the type now entering commercial production can yield 315°C process heat in average US isolation at an uninstalled retail price of about \$118/m^2 (7, 27; see also 75). Many clever methods of one- and tow-axis tracking are also being rapidly developed and brought to market. For very-high-temperature (*k*°C) process heat, the heliostats being developed for "power towers" show promise, especially in relatively simple modular arrays (78) of which one form is commercially available from ANSALDO SpA of Genoa (27). Tracking parabolic dishes, such as the Jet Propulsion Laboratory's design which is expected to cost \$135/m^2 installed, can also achieve high concentration ratios ($\sim 10^3$) and high temperatures (~815°C). They appear competitive (in electrical applications) with large heliostat fields (79). Cruder devices can be much cheaper: Hayes (80) reports an effective solar cooker selling in India for \$4.40/m^2. More complex solar cookers are sold in the USSR (81). Some important applications, such as desalintion and crop drying, can often use low-grade solar heat already available at \$2–4/GJ (less in very simple devices). Local heat storage up to 315°C in organic liquids (27) and higher in liquid salts, metals, or refractories is straight forward and can use commercial hardware. All high-temperature solar systems can improve their economics by cogeneration, and many can do so by including district heating too.

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[12] AB Östgötabyggen plans to start building in 1978 at Linköping a 50-house scheme with ~10^{4}m^3 of storage at ~\$25/m^3, and Sunvex (Växjö) has somewhat similar plans. P. Margen (AB Atomenergi, Studsvik), who is building a small pilot scheme in 1978, has also proposed cheaper storage by curtaining off part of a lake (P. Margen, personal communication and unpublished papers, 1978).

Fluid fuels

The sunlight captured by photosynthesis in crops and trees is currently the largest single energy input to the US economy. Farm, forestry, and municipal wastes,[13] already available and usually harvested, can probably yield ~6 EJ/year ($\sim 6 \times 10^{18}$ J/year) net fuel in the United States (82, 83), ample to run in 2025 a US transport sector approximately 3 times as efficient as the present one (2, 5). Similarly adequate yields appear possible in most other regions, though possibly not in all countries The conversion method of choice in the long run may be enzymatic digestion, but in the short run it is mainly pyrolysis (84), especially for wood and fibrous crop wastes.[14] Delivered fuel alcohols are widely estimated to cost ~\$2–4/GJ from municipal and many crop wastes, ~\$3–6/GJ for other renewable feedstocks. While some microeconomic assessments find conversion of forestry wastes to methanol (without byproduct credits) to be slightly dearer than historically cheap gasoline (85), broader analyses (86–90) suggest a bright future. Some biomass-conversion systems, mainly for anaerobic digestion of feedlot manure to pipeline gas, are already being demonstrated in North America. A biogas plant producing 240 net m^3/day is to become commercially available in Denmark in 1978 at an installed price of DKr 100,000 (~\$19,000 (1976 \$) ~\$21,000/bbl.day) (O. Albertsen, personal communication, 1978). Biogas plants are an important development tool (91, 92), which is why China has installed over 4 million since 1972 (2, 80; T. B. Taylor, personal communication, 1977). A major fuel alcohol program based on sugar cane and manioc (using enzymatic hydrolysis for the latter) is under way in Brazil (93, 94), selling ethanol profitably from inefficient distilleries at a price ~2–3 times the average 1977 taxed retail price per GJ of US premium gasoline (through blended alcohols can improve average vehicle km/GJ).

Current studies of proposed wood-fired power stations in northern New England (95–97), the Pacific Northwest, and the Maritime

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[13] A useful survey is the January 1977 Symposium *Clean Fuels from Biomass and Wastes*, whose proceedings are available from the Institute of Gas Technology (Chicago).

[14] J. W. Tatom (4070 Ridge Road, Smyrna, GA 30080) has developed a remarkable range of fixed and mobile pyrolyzers for the United States, Senegal, Ghana, and Indonesia. His detailed and empirically verified design calculations show that a 100-dry-ston-input/day mobile plant costing (in 1977 \$) a liberal \$700,000 (\$6,000/bbl.day net output) could produce char-oil from free, 50%-wet sawdust, with no disposal credit, at a total cost of \$0.8/GJ in three- and \$1.1/GJ in two-shift operation 250 day/year.

Provinces suggest they are already attractive at modest scale. Further possibilities might include not only combined-heat-and-power stations but also, perhaps, taking off midcycle process heat for pyrolysis and producing methanol or charoil as a third output. Copyrolysis might also be possible at pulp mills, for which alcohol is an attractive output because it can be sold at just below the OPEC price. Solar process heat, too, has been suggested (98) as an adjunct to bioconversion. While monocultural biomass plantations for fuel or feedstocks seem ecologically unattractive, some preliminary analyses are surprising: $\gtrsim$ 12 EJ/year of methane at \$2.2–6.5/GJ (and $\sim\$5\times10^4$ investment per bbl/day output) from California kelp, for example (99), and cheap bulk glycerol (~\$3–11/GJ) from Dead Sea algae (100), and a prospect of various hydrocarbons from arid-land species of such genera as *Euphorbia* (under study by Melvin Calvin's group and others).

Mechanical work at fixed sites

Microhydroelectric plants (see below), solar heat engines (27, 56), and wind machines (see below) can pump water or heat and can compress air to drive industrial machinery. These important applications are receiving little official attention despite the widespread past use of wind for pumping and milling. Ocean-wave collectors, under extensive study in Britain, also offer much in sutiable sites if their engineering problems prove as tractable as hoped. The wave concentrator concepts developed by E. Mehlum (Sentralinstitutt for Industriell Forskning, Oslo) look especially promising.

Electricity

To US hydroelectric capacity now built or being built (~63 GW) and the refurbishing and fuller use of existing big dams (most of ~28 GW) can be added ~27 GW of cheap (~\$3–1200/kW) microhydroelectric capacity (units of a few kW to 5 MW), much of it in small dams from which turbines were removed in recent decades, and the rest in run-of-the-river sites requiring no dams (101, 102). There is also a potential for up to an additional ~32 GW of new small-scale dams (84). Several GW of microhydroelectric capacity, mainly at $\sim10^3$—10^4-W scale, now supplies most of the electricity for rural China (103, 104).

The aerospace community envisages high-technology wind-electric machines of MW capacity costing of the order of \$400–600/kW(e) peak and yielding 2–4¢/kW-hr electricity in typical windy-site wind regimes averaging 7 m/sec (105–108). (Some observers estimate slightly higher costs.) But large machines, even if better designed than the >\$5,000/kW(p) (kilowatt of peak output) ERDA/NASA prototype (109), may have more severe materials problems than small machines owing to greater blade stress and vibration. Though technical lead times are only 1–2 years, such big machines are also accessible mainly to utilities and can be mass-produced only in the same sense as large jet aircraft, so they may be slower to deploy than small Model-T-style machines in the spirit of those that used to dot the Great Plains (such as the Jacobs machines, many of which are now being resurrected and overhauled so that they can send out <3–6¢/kW-hr electricity for another 30 years.) Perhaps a more promising design approach is illustrated by a 17-kW(p) (in 17 m/sec wind), 6-m diameter Chalk-wheel machine that two people can bring home in a pickup truck and put up in 15 hours on a bolt-together tower, using only two crescent wrenches and a screwdriver. Such a machine has been homemade for $1500 and has an estimated mass-production cost (with tower) of about $5000 ($295/kW(p)), yielding ~2–3¢/kW-hr in 6–7 m/sec average wind (110; O. J. M. Smith, unpublished data). Smith estimates there are over 200,000 identified sites in rural California alone (4), and plausible deployment rates on the Great Plains might be of the order of several GW/year.

Unofficial wind programs show the same wide range of costs as solar collectors. Reported values include $350/kW(p), not counting much contributed labor (B. Sørensen, personal communication, 1978), for the Tvind (Denmark) 2-MW machine, the largest in the world, finished in 1978 as a school project (111–112); ~$760/kW(p) (price, 1978 $) for complete, recently installed 22.5-kW machines sold by Riisager El-Windmølle (Skaerbek, near Herning, Jutland) (prices FOB factory are ~DKr 60,000, or 40% less); DKr 36,000 (factory price), or ~$310/kW(p), for two simpler 20-kW machines sold by Niels Borre (L. Albertsen, personal communication, 1978); ~$1050–1350/kW average (estimated installed cost) (113) for a built-today version of the successful 200-kW Gedser (Denmark) machine (now being revived); substantially under $1000/kW(p) (installed 1978 price) for a 200-kW updated Gedser machine recently installed by WTG Energy Systems (Angola, NY) on Cuttyhunk Island, MA; ~$250/kW(p) (estimated 1979 retail price including tower) for the 25-kW(e) hydraulic-drive machines to be sold at cost by Charles Schachle (Moses Lake, WA); $205/kW(p) for the 1978 installed commercial price of 3-MW machines subsequent to the first unit sold by Schachle in spring 1978 to Southern California Edison for $356/kWp (including first-unit design costs); $500/kWp (factory cost) for a typical 4-kW system (114); ~$50/kW(p) (materials cost only) for a typical small machine homemade from old car parts; and about $750/kW(p) for the run-on installed price corresponding to the 200-kW Darrieus machine of Dominion Aluminum Fabricating, Ltd. Missisauga, Ontario, which operates on the Magdalen Islands for Hydro-Québec (2; cf 115). The costs of electricity even toward the top of this range seem competitive with marginal and sometimes with historic values, especially if dispersion credits are taken into account. Substantial commercial ventures are therefore beginning. Wind would normally be run baseloaded (116) and used as a fuel saver on the grid during the fossil-fueled transition period, then peaked with hydro in a soft-technology economy. Though it is irrational to use wind machines to imitate reactors, the costs of doing so are surprisingly low (117–119): a mere 10 hours' storage makes a typical Danish wind machine into as reliable a source of firm power as a typical light water reactor (117).

Solar heat engines (27) may already be economically attractive at the margin. One vendor (Kinetics Corp., Sarasota, Florida (56)) is reported to be profitably offering 1.25 MW(e) Rankine engines, 10% efficient on 85°C hot water ($\Delta T \equiv 63°C$), for $800/kW(e) (1978 $). Costs per kW(e) are of course lower (27) at higher working temperatures, and mass-production cost estimates are an order of magnitude lower still (27, 74). If even better heat engines (based on Stirling, Ericsson, Rankine, or Brayton thermodynamic cycles) are developed for bottoming cycles or ocean-thermal-electric systems, they should find even readier application with solar heat from collectors, ponds, or photovoltaic coolants, all probably dispersed.

Photovoltaic devices are nearing widespread commercial use much faster than expected (120, 121). The US Department of Energy's 1986 price goal of 50¢/W(p) (1975 $) may be surpassed. (The 1978 array price for handcrafted silicon cells is $11/W(p)—perhaps as low as $8/W(p) (1975 $) for orders of a few hundred kW.) There is persuasive evidence that merely ordering Czochralski silicon at a level (>150 MW(p)) now justifiable for remote military sites would, by the use of present mass-production technology, quickly lower its price well below that of nuclear power (122, 123). Efficiency of materials use, quality control, and field durability need and are getting skilled attention. Sophisticated concentrating devices are now entering commercial production. Research on GaAs (cf 124), thermophotovoltaic cavities (125), photoconversion dyes, multiple-junction cells, and coarse polycrystalline silicon (126) proceeds at an astonishing pace. These developments may even be overtaken by amorphous materials (127, 128)—not necessarily those of S. R. Ovshinsky of Energy Conversion Devices, Inc., Troy, Michigan, but perhaps silicon deposited from silane vapor (129, 130). As for the more toxic CdS/Cu_2S cells, Patscentre International Ltd. (Melbourn, Herts., UK) claim to be able now to make 2-μm-film wet-sprayed CdS assemblies, $\geq 4\%$ efficient, robust, sealed, and free of degradation in accelerated-lifetime tests equivalent to 8–9 year, for a commercial price of £ 5.8/m^2 (1977 value), or $10/$m^2$ (1976 $), corresponding to about 25–30¢/Wp, a highly competitive level (2; G. Edge, personal communication, 1978). Two US firms are working with CdS; one can reportedly produce cells at a roughly comparable cost (27) but has sold at a far higher price and has had degradation problems which Patscentre appear to have avoided.

Though published soft path analyses (2, 4) have not assumed photovoltaics, so many promising approaches are already apparent that it would be surprising if several kinds of competitive photovoltaics were not on the market within the lead time of recently ordered power stations. It is even possible that future, especially amorphous, devices may compete not only with central-station electricity but also, perhaps via electrolysis, with historically cheap fuel. If so, their dispersed use could justify expansion of electricity well beyond its thermodynamically necessary share (2).

Bulk electrical storage is difficult and poses a formidable problem for a hard energy path—a problem whose solution, perhaps by proxy thermal storage (118), would make soft systems even more attractive. Electrolytic and fuel-cell systems (even more convenient if direct solar photolysis becomes commercially available), such systems plus hydride storage, flywheels, cryogenic heat-engine "fuels" such as liquid air, and compressed air are among the most interesting approaches. Yet in a soft path, bulk electrical storage would in general not be necessary; wind, and perhaps photovoltaics, below the baseload shoulder of the load-duration curve would be peaked with macro- and microhydroelectricity. Local electrical storage, e.g. in batteries, could be useful if dispersed photovoltaics were widely used, especially if users switched end-uses to low-voltage direct current rather than connecting to the grid via synchronous inverters[15] and reversible meters; but this scale of storage does not seem difficult. Using electricity only for applications requiring it, and readily stored direct heat and fuel alcohols for the other 90+% of end-use needs, should make the energy storage problem tractable in a soft path.

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[15] Using dispersed chip-controlled inverters for microcontrol of the grid raises intriguing control-theoretic problems akin to those of neurophysiology, ecology, and telephone network synchronization (131).

COMPARISONS

Though even first attempts at comparing hard and soft energy technologies are difficult and easily mired in details (2, 5), several broad arguments suggest that soft technologies, and soft energy paths, are superior to their alternatives with regard to costs, deployment rates, risks, domestic sociopolitical effects, and geopolitics.[16]

Costs

External social costs of energy technologies are probably more important, both in theory and in political practice (3), than private internal costs. Nevertheless the latter will be assessed here for people who think them decisive. Since all future costs are uncertain, empirical data will be used for virtually all technologies. Conservatisms will be weighted in favor of hard technologies (2), both in base-cost data and in omission of structural trends that are likely to make hard technology costs rise and most soft technology costs fall or at least rise more slowly. [This assumes that even if long-term escalation is greater for labor than for materials, the relative benignity of the soft technologies will be more important (43)].

Contrary to present practice, all technologies will be symmetrically compared with each other. Traditionally, hard-technology costs are compared with each other while soft-technology costs are instead compared with the subsidized prices of the cheap fuels that all kinds of marginal supply are meant to replace. When, as now, we are told that we must invest in power stations and synfuel plants because it will take decades to build enough of them to provide timely and significant substitution for dwindling oil and gas, it is the costs of those hard technologies, not of the oil and gas, with which we should compare the costs of soft technologies. The long-run margin is already here (133).

A useful data base can be assembled (2) by calculating whole-system capital costs to deliver marginal enthalpy at a given rate [taken here to be 1 bbl oil equivalent, or 5.8 GJ, per day, or about 67 kW(t)].[17] Capital intensity is a useful first-order signal for energy price, in which it is generally the dominant term for all marginal sources, but unlike fuel price, it is an engineering number relatively resistant to the interfering effects of tax, regulation, and oligopoly. Capital intensity is also an early-warning signal in times of capital constraint, and, if lower for a solar than for a fueled technology, implies the former will have a lower energy cost too.

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[16] J. Weingart has argued (132) that a hard energy path based entirely on solar technologies may also be more attractive than its nuclear counterpart.

[17] The unit \$/(bbl-day) pays tribute to the oil-major strategic planners who first studied these whole-system costs.

Such a comparative table of illustrative capital costs is given in Table 1, which emphasizes the relatively low and high capital costs, respectively, of improved end-use efficiency and of electrical systems, compared to any direct-fuel or direct-heat systems. Table 2 uses the data from Table 1, and noted assumptions about operating costs and and the cost and First Law efficiencies of end-use devices, to compute illustrative prices of delivered energy in various forms from various systems. The results strongly suggest that though soft technologies are not cheap, they are cheaper than not having them; that though they may or may not be cheaper than present oil and gas, they are generally cheaper than the things one would otherwise have to do to replace present oil and gas (especially beyond the 1990s); and that of all alternatives ranked together, the cheapest are the end-use efficiency improvements, then the soft and transitional technologies, then (usually) synthetics, and last (costliest) central-electric systems. This conclusion appears robust against further refinements in the data and calculations, owing to consistent conservatisms[18] (2). Analysts who do not accept this must at least agree that the traditional dogma about soft technologies being much costlier than hard is not obviously sustainable.

TABLE 1.—APPROXIMATE MARGINAL CAPITAL INVESTMENT FOR COMPLETE ENERGY SYSTEMS DELIVERING 1 BARREL PER DAY [67 kW(t)] ENTHALPY TO U.S. CONSUMERS[1]

Energy system	1976 dollars/ (barrels per day)[2]	Form supplied[3]
Hard technologies:		
Traditional direct fuels, 1950's–1960's[6] or direct coal, 1970's	2 to 3,000	F
North Sea oil late 1970's[5]	10,000	F
U.S. frontier oil and gas, 1980's	10 to 25,000	F
Synthetic from coal or shale, 1980's	20 to 40,000+	F
Central coal-electric plus scrubbers, 1980's	170,000	E
Nuclear-electric (LWR), mid-1980's[6]	235,000+	E
Technical fixes to improve end-use efficiency:		
New commercial buildings	−3,000[7]	HE(?)
Common industrial and architectural leak-plugging; better home appliances	0 to 5,000[7]	HE
Most heat-recovery systems	5 to 15,000[7]	H
Bottoming cycles; better motors[7]	20,000[8]	E
Worst-case, very thorough building retrofits	30,000[7]	H
Transitional fossil-fuel technologies:		
Coal-fired fluidized-bed gas turbine with district heating and heat pumps (COP=2), early 1980's.	30,000[7]	H
Most industrial cogeneration, late 1970's[8]	60,000	EH

See footnotes at end of table.

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[18] These include in, for example, the solar heat versus nuclear case low nuclear costs, no allowance for cheap solar designs, (passive, integrated, neighborhood, ponds, etc), high fixed charge rate, no allowance for cash-flow differences or differential escalation, and peak-load heat-pump efficiency overstated by a factor of approximately 2.5. Low-technology approaches, stated by Taylor (56) to be competitive with most present forms of energy in most parts of the world, are also not considered.

TABLE I.—APPROXIMATE MARGINAL CAPITAL INVESTMENT FOR COMPLETE ENERGY SYSTEMS DELIVERING 1 BARREL PER DAY [67 kW(t)] ENTHALPY TO U.S. CONSUMERS [1]—Continued

Energy system	1976 dollars/ (barrels per day) [2]	Form supplied [3]
Soft technologies:		
Passive solar heating ($\leq$100 percent);	< to 20,000 [7]	H
Retrofitted 100 percent solar space heat, no backup needed, $\sim$100-unit neighborhood.	$\sim$20 to 40,000 [7, 9, 10]	H
Same, single house, mid-1980's	$\sim$50 to 70,000 [7, 10]	H
300 C solar process heat, 1980 [11]	120,000	H
Collection and bioconversion of farm and forestry wastes to fuel alcohols, 1980	<15 to 25,000+	F
Pyrolysis of municipal wastes, 1980	30,000 [12]	F
Microhydroelectric plants [13]	30 to 140, 000	E
Solar pond and Rankine engine [14]	120,000	E
Wind-electric plants 15	$\sim$70 to 185,000	E

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[1] Data derived in (2) chs. 6–8; see also chs. 1, 3, except as noted in footnotes 8, 9, 13, and 14 and conservation costs (derived from a wide range of literature, partly cited in (2)).

[2] Empirical data except synfuels (projected), fluidized-bed gas turbine (price of turnkey offer), and solar neighborhood heating (footnote 9).

[3] F=fuel, E=electricity, H=heat.

[4] Not marginal; included only as baseline for comparison.

[5] For details, see (2) ch. 6. Briefly, assumes 1.1-GW(e) LWR ordered in 1976, at a price of $585 per net installed kW(e) (1974 dollars; Bechtel data) converted to $929 (1976 dollars) with the Bupp & Treitel current-dollar index of 1.26 per year. Real escalation after 1976 assumed to be zero. Marginal fuel-cycle, transmission and distribution facilities priced respectively at $61, $69, and $420 per kW (1974 dollars; Bechtel data), converted to $76, $86, and $525 respectively (1976 dollars) with the 1.25 Marshall & Stevens Equipment Cost index. Assumes front-end cost of $100 per kW (1976 dollars) for initial core. Total investment, $1,716 per kW(e) installed, converted to $3,120 per kW(e) sent out by dividing by 0.55 nominal capacity factor, then to $3,495 per kW(e) delivered equal $234,500/(bbl/day) enthalpy delivered by surcharging 12 percent for equivalent 10.7 percent losses in transmission and distribution. These data are generally conservative (too low). Omitted costs include marginal capital investment in land, reserve margin, Federal regulatory and security services, Federal R. & D., future services (waste management and decommissioning), and end-use devices; allowance for real cost escalation after 1976 (presently about 20 percent per year for LWR's and 7 percent per year for coal stations); the 6.5–8 percent of output needed to operate the fuel cycle; and all externalities and dynamic net-energy considerations. Including realistic estimates for all terms (except for last two and end-use devices) might raise the total to $\geq$$5,000 per kW(e) delivered.

[6] Includes the often high cost of end-use devices. An unpublished 1976 Shell analysis calculates typical investment per bbl per day used of the order of $120 to $200,000 for a European car, $35,000 for a conventional house heating system $5 to $10,000 for industrial boilers, and $14,000 for a blast furnace.

[7] Calculated from the review by G. N. Hatsopoulos, T. F. Widmer, E. P. Gyftopoulos, and R. W. Sant, "A National Policy for Industrial Energy Conservation," published by Thermo-Electron Corp. (Waltham, MA), Apr. 22, 1977. Assumes that both topping and bottoming cycles use both process heat and electricity inside the plant, avoiding marginal investment in electric distribution facilities.

[8] Estimated from following entry and (55), with extra allowance for heat distribution in fairly low-density settlements.

[9] Assumes that, in accordance with economic priorities, stringent heat-conservation measures have been applied first. Assumes traditional flat-plate collectors (not integrated into building fabric) with sensible heat storage in water in $\sim$$25/m^3 tanks of modular concrete slabs (70). For cloudy high-latitude sites (e.g. Scandinavia), add about 40 percent to upper values. See (2, 68) and discussion in text.

[10] Retail price $118/$m^2$ (7) for 315°C, 0.44-efficient Winston collector; installation price $22/$m^2$. See also text.

[11] Excludes investment credit for byproducts (e.g. materials recovered) and for waste disposal services replaced. Much lower costs are possible: specific investment for Tatom's mobile pyrolyzer (text, footnote 14) is approximately 5 times lower.

[12] Based on unpublished draft estimates by CEQ, MITRE, and New England Regional Commission ($3–1,200/kW(e) installed with average capacity factor $\sim$0.6–0.7), 5 percent distribution loss, and zero marginal transmission capacity (owing to old lines still available at old dam sites). See Huetter, J. 1978. "Status, Potential and Problems of Small Hydroelectric Power Development in the United States." Unpublished report to President's Council on Environmental Quality, Washington, D.C., 66 pp.

[13] Pond costing $10/$m^2$ with 0.65 efficiency; Rankine engine plus local distribution (see text) $800 per kW(e); 10 percent engine efficiency (conservative, as the pond should yield 90–105°C, not 80°C); 4 percent distribution loss; 0.95 capacity factor using heat storage in pond. Land cost not included.

[14] Upper value from Riisager 22.5-kW(e) machines, lower from run-on Schachle 3-MW(e) machines, at $760 per kW(p) and $205 per kW(p) respectively (1978 dollars; see text); deflated to 1976 dollars with 0.87 index; for both, 0.3 capacity factor, 4 percent distribution loss, and a third of the $\sim$$380/kW$\leq$600-VAC distribution investment assumed marginal. Storage investment omitted, based on fuel- or water-saver operation in a hydro-peaked grid (see text). 10-hour storage—sufficient (117) to make a typical Danish wind machine into as reliable a source of firm power as a typical U.S. LWR—might add about $180 to $230 per kW(e) sent out to capital cost and have 20–30 percent losses. In practice it is very doubtful such storage would be needed. See B. Sorensen, "The Regulation of an Electricity Supply System Including Wind Energy Generators," preprint for 2d International Conference on Wind Energy Systems, Amsterdam, 1978; and E. Kahn, "Reliability of Wind Power from Dispersed Sites: A Preliminary Assessment," Draft Rep. No. LBL–6889 Lawrence Berkeley Laboratory, April 1978.

TABLE 2.—APPROXIMATE PRICES OF DELIVERED ENERGY FROM VARIOUS U.S. ENERGY SYSTEMS [1]

Type and system	1976 (dollars per GJ)[2]	1976 dollar/ barrel crude oil eqiuvalent [2, 3]
Raw fuels:[4]		
Natural gas	1.9	11
Coal	2.1	12
No. 2 fuel oil	2.8	16
Propane	4.4	25
Taxed regular gasoline	5.3	31
Electricity	8.7	51
Space heat:		
Improved end-use efficiency [5]	−.2 to 1.4	−1 to 8
100 percent solar (neighborhood) [6]	1.2 to 2.5	7 to 14
Natural gas [4, 7]	2.8	16
No. 2 fuel oil [4, 7]	4.1	24
100 percent solar (house) [6]	2.9 to 4.1	16 to 24
High-Btu syngas [8]	5.0 to 6.4 [9]	29 to 37 [9]
LWR/heat pump [10]	7.4	43
LWR resistive [11]	17.5	101
Process heat:		
Coal [4, 12]	2.8	16
High-BTU syngas [8, 9, 12]	6.2	36
300° C Winston solar [13]	7.3	43
Fluid fules: Bioconversion [14]	1.4 to 4.8	8 to 28
Electricity:		
Microhydroelectric [15]	1.7 to 8.0	10 to 46
Solar pond and Rankine engine [16]	6.9	40
Wind [17]	10.5 to 17.2	61 to 100
LWR [11]	17.5	101

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[1] Illustrative values based on table 1 and assumptions noted below.

[2] Marginal prices except as noted in footnote 4: capital investments converted to capital component of energy prices at 0.12/year fixed charge rate, which is high (therefore unfavorable to renewables) for the constant-dollar accounting used here, bearing in mind that utilities' income tax on revenues from marginal investments is generally zero or negative (171).

[3] Equivalent crude oil at 5.8 GJ/bbl converted at 1.0 first law efficiency; e.g. in practice (footnote 7) the LWR/heat pump system would compete with $43×0.7=$30/bbl oil (neglecting refining).

[4] Approximate average of U.S. regions (not weighted by consumption) at end of 1976; not marginal but shown as baseline. European prices tend to be much higher.

[5] Aggregation of categories in table 1.

[6] Assumes average U.S. insulation (180 W/m² average over all states of the earth's rotation and orbit); for cloudy high-latitude climates (e.g. Scandinavia), add about 40 percent to higher values. Assumes extremely energy-efficient buildings retrofitted with insulation and recuperators before solar system Mid-1980's solar system installed price $100/(m²+m³) and storage 0.4—0.5 m³/m² collector for single house. Lower prices are possible with innovative collectors or new buildings. Assumes 10¢/GJ for operation and maintenance (O. & M.).

[7] Fuel price as above; free with 0.7 first law efficiency and 2 percent O. & M. charge.

[8] Assumes gas system capital cost $40,000/(bbl. day) delivered, working at 90 percent capacity factor; 57¢/GJ mine-mouth coal converted at 58 percent efficiency with operating costs (less byproduct credits) of 10¢/GJ and same delivery cost in free pipelines; no water constraints; combustion as in footnote 7.

[9] Higher value assumes that furnace and pipeline are assigned marginal capital costs of 28¢ and a conservative 95¢ per GJ respectively. Gas prices shown are probably $\gtrsim$$1/GJ too low.

[10] Electricity price from footnote 11; $200/kW(e) heat pump with an average and winterpeak COP that equals 2.5 (exaggerating the probable capacity saving by a factor of 2.5, since most heat pumps have a COP of approximately one and add resistance heaters on the coldest days); 2 percent O. & M.

[11] Fuel-cycle cost at empirical burnup (credited for initial core), O. & M., and taxes for station conservatively assumed to be 7.2. 1.5, and 0.4 m$/kW-hr respectively; 6 m$/kW-hr for O. & M. on transmission and distribution capacity. Delivered electricity price, 63 m$/kW-hr, is conservative for reasons explained in table 1, footnote e, and because nonnuclear (e.g. peaking) plants, allegedly inferior in the merit order, would produce even more expensive electricity. Present electricity prices are typically somewhat below this level in industrial countries, several times it in many developing countries.

[12] Assumes $8,000/(bbl. day) fuel-used furnace with 0.8 first law efficiency and 2 percent O. & M. Coal price from top of table is current, not long-run marginal.

[13] Assumes (table 1) installed price $140/m², with 180 W/m² average insulation, 0.44 first law efficiency, 2 percent O. & M., and 50¢/GJ buffer storage (including its losses as an equivalent surcharge). Highly selective flat plates or tubes—especially with a roof replacement credit—would probably be cheaper.

[14] Marginal collection and operating costs $0.5—3.6/GJ net output.

[15] Lower values characteristic of sites with existing dams; higher, of derelict or run-of-the-river sites.

[16] Assumptions as in table 1, footnote m, plus 4 percent O. & M. The capital cost of the engine [$673/kW(e)] is close to the 1978 Kinetics Corp. price deflated to 1976 $(~$700; see text) and well above prices expected for mass production (27).

[17] Range of captal costs from table 1, adding 4 percent O. & M. and 10 hr. of storage at $50/kW(e)-hr. The storage costs component is $6.3/GJ. Wind electricity integrated into a hydro grid (table 1, footnote 14) is therefore around the $4.2—10.8/GJ range.

Rates

The thesis that we must build many synfuel and central-electric plants to bridge the "gap" before soft technologies can make a large contribution ignores the formidable rate-and-magnitude problems of hard technologies with long lead times (11,134), and hence the "gap" while hard technologies are being deployed. Two arguments suggest, however, that regardless of a country's access to transitional fuels, a dollar invested in soft technologies today may yield more energy, money, and jobs (2) faster than a dollar invested in hard technologies.

First, soft technologies are simple enough to have technical lead times measured in days, weeks, or months, not ten years. The cycle of development, demonstration, and deployment can thus be vastly condensed, very many approaches tested in parallel at low unit cost and risk, and existing industrial capacity readily adapted for production. How far we can overcome social constraints and so achieve the short technical lead times is not firmly known, but some anecdotes (2) are suggestive: for example, 40% of all Vermont houses, including many in towns and cities, were retrofitted by their owners with wood-burning iron stoves in three years, while in five years the fraction of US households trying to grow some part of their own food rose from 20% to 50%, again through private initiatives. These and similar examples—deployment of, say, snowmobiles or citizens'-band radio—suggest that people can do many small things for themselves very quickly if they have incentive and opportunity.[19] Soft technologies fit this pattern. They are directly accessible to orders of magnitude more users than hard technologies are (11). Soft technologies do not need (indeed, probably cannot tolerate) elaborate central management, but need only a clearing of institutional barriers that include inequitable access to capital (135), and the use of symmetrical economics, or long-run marginal-cost pricing, to implement themselves through existing market and social processes (2, 5). the diversity of soft technologies is another reason that they are quick to deploy. Their aggregate contribution (Figure 2) is made up of dozens of quite different technologies with generally independent rate constraints. The things that hold back passive solar heat in new houses are not the same that hold back microhydro or solar crop drying or woodlot pyrolysis. Therefore, rather than having a few monolithic technologies held back by generic constraints, one has dozens of relatively slow-growing wedges adding up—by sheer strength of numbers—to very rapid total growth, speeded by soft technologies' avoidance of serious political constraints (see below).

Figure 6, due to N. Nakicenovic and J. Weingart (IIASA), plots C. Marchetti's historic data and projections for US use of fuels on a logarithmic scale of fractional market penetration (with post-1970 fuel data not meant to correspond to the estimates in Figure 2). On the right, drawn on two slightly different assumptions, is the soft technology penetration rate sketched in Figure 2. The slope does not appear unreasonably steep in view of the simplicity, short lead times, and diversity just described. Moreover: (*a*) the decreasing slope of

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[9] Likewise on a national scale, as in the British conversion to smokeless fuels and North Sea gas, the Dutch conversion to Groningen gas, the conversion of several Canadian cities and Los Angeles to 60-Hz electricity and of many Scandinavian towns to district hearing, and the complete conversion of most countries' car industries in about six to nine months during the early 1940s. Each year the U.S. automobile industry now makes cars whose total peak power is roughly a half or a third of total present U.S. energy use.

successive historic fuel penetrations suggests that the increasing technical simplicity (134) of the successive sources at large scale—wood, coal, oil, gas—was more than offset by the difficulty of penetrating an exponentially growing market, whereas the market penetrated by soft technologies would be stabilized and even declining (Figure 2); (*b*) the soft technology penetration rate shown is in the upper-mid-range of those in the literature (2) even though no other analysis assumes symmetric cost comparisons nor rapid clearing of institutional barriers (e.g., by capital-transfer schemes (135) nor an approach to long-run marginal-cost pricing via an anticipatory price schedule that short-circuits several decades' lag ("dead period") at the start of the normally assumed slow exponential rise in fuel prices; (*c*) the soft technology rate shown is slower than, and thus presumably more plausible than, virtually any official nuclear projections.

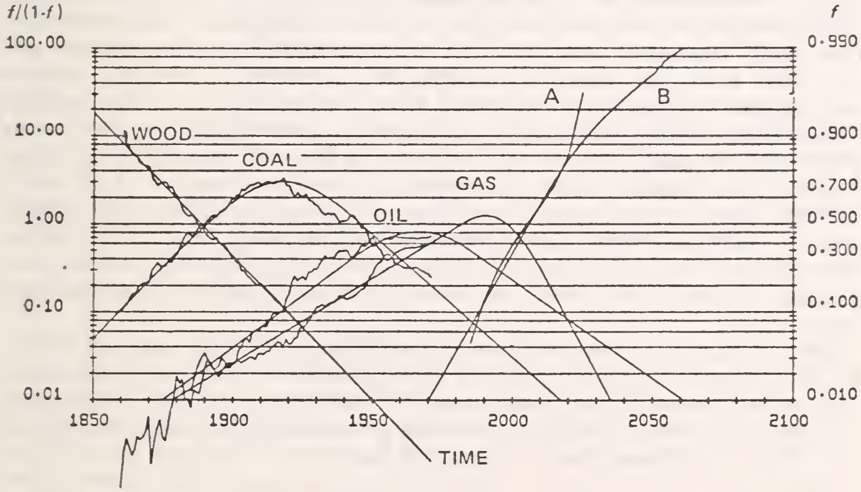

FIGURE 6.—Fractional penetration *f* of US commercial energy market vs time Historic data of fuels to 1970, projections by C. Marchetti thereafter; the two curves *A* and B toward the right, plotted in two slightly different ways by N. Nakicenovic (IIASA), show the approximate penetration curve for soft technologies estimated in Figure 2. (Fuel curves after 1970 are not meant to conform to Figure 2.)

Risks

The diversity, simplicity, and proven performance of soft technologies make their risk of technical failure lower than that of relying on a few big high technologies, like breeders and high-BTU coal-gas complexes, that are not here and may or may not work. Tables 1 and 2 also assume soft technologies as reliable to the user as present systems, but this may be an unfair comparison: the present electric grid must be so expensively reliable (136) because its failure is such a social calamity. If your solar heater failed (unlikely, as there is little to go wrong) you might not notice for a few weeks, owing to high thermal integrity and seasonal storage; but even then you could put on a sweater or go next door, whereas when the grid fails there is no next door. This difference in the nature and extent of consequences suggests that dispersed, more resilient (46) systems with local storage may deserve a different approach to defining end-use reliability—one more oriented toward heterogeneous end-use needs. Indeed, it could be considered a diseconomy of the central-electric grid that since it cannot distinguish different users' differing needs for reliability, owners of water heaters must pay for the reliability needed by subways, elevators, and hospitals. The same is true of diverse requirements for voltage stability and phase coherence.

Soft technologies, on preliminary but persuasive analysis, appear more environmentally benign than hard technologies (including centralized and electrified renewables) (137, 138) and their side effects more amenable to technical fixes.[20] The same is probably true of health and safety impacts: the risk of falling while cleaning a rooftop solar system, for example, could be reduced by long-handled sponge-mops (137). The main type of environmental harm by poorly conceived or poorly managed soft technologies might be to degrade soil structure or ecology (especially in the tropics and subartic) or to deplete micronutrients (139) through biomass-residue harvesting practices that do not respect ordinary principles of good husbandry. Long experience of sustained yields in farming and forestry offers confidence that such harm can generally be avoided, but details for each site will need careful study and management. Further, if, as assumed above (2, 5), only present farm, forestry, and municipal wastes are used, rather than special biomass crops, then marginal use of land, water, and other factor inputs to agriculture will be essentially nil; indeed, careful integration of energy and food (or forestry) systems might even increase productivity.

Soft energy technologies have no significant climatic impact (137). In particular, the carbon cycle of biomass use is "on current account" and so climatically inconsequential. A soft energy path hedges our bets on the serious climatic problems of combustion products such as CO_2 (2) by minimizing the integrated fossil-fuel burn and by reducing the ratio of CO_2 input rate to CO_2 absorption rate. The timing of the CO_2 problem—at whatever CO_2 level it may arise—is remarkably insensitive to whether or not nuclear power is used, but highly sensitive to demand-stabilizing efficiency improvements.

Sociopolitics

Soft technologies can avoid virtually all the high political costs of hard technologies, including centrism, vulnerability, and technocracy. This key issue is treated at length elsewhere (2). Soft technologies have their own political problems, such as adapting to the idea of relying mainly on hundreds of millions of private choices in devices and refinements, rather than on a few big, difficult projects run from Washington. For people who think central management is more part of the energy solution than part of the problem, this may be a traumatic adjustment. A soft energy path also requires that a long, messy list of institutional barriers be cleared away at local and state level—a difficult task indeed. Yet it seems easier than not doing it, and is essential in some form to any energy policy, hard or soft. Indeed, clearing the "institutional barriers" peculiar to a hard path, such as nuclear siting and regulatory problems and the refusal of the market to fund most hard technologies, appears to present far more intractable problems. Desubsidization and a gradual, equitable move to proper pricing of depletable fuels (2), both of which measures are essential for a soft path, are also not easy, since some people believe there is a free lunch (135); but the hard-path alternative of paying for energy everywhere else in the economy, e.g. through inflation, unemployment, and environmental damage (2), is an even knottier political problem. In this sense, the ability of a soft path to benefit virtually all constituencies at once, rather than only a few, is a great advantage (2).

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[20] A heretical minority might even ask whether some wind machines' potential interference with TV reception is a cost or a benefit.

Most countries, especially the United States, are full of diver people unable to agree about the nature of the energy problem, th the role of governance and of price, the future of big oil companies, and the desirable direction of social evolution. If resolving these conflicts is a prerequisite to addressing the energy problem, hell will freeze over first. But the soft path, being relatively motive-free, welcomes rather than fights this diversity. An economic traditionalist can build a solar collector because it is cheaper than not doing so; a labor unionist, because it gives more and better jobs than building power stations; a conservationist, because it is benign; a social transformationalist, because it is autonomous; but it is still the same collector, and they need not agree on why they are building it. Likewise given that we have a strong consensus that soft systems and energy husbandry are desirable, a substantial consensus on the limited clean use of coal, but no consensus on anything else, a soft path adds up the bits people agree about, because they are enough, and ignores the rest because they are superfluous. We have never tried to design an energy policy around consensus, but it seems time we started.

Finally, in a period of uncertainty and perhaps of incipient social transformation (138, 140–144); soft technologies decrease risk. It is arguable (C. Bullard, personal communication, 1977) that there is a basic incompatibility between high-impact, long-lead-time technologies and US constitutional structure. A utility investing $\$10^9$ in a reactor today, for example, wants to be certain it can get an operating license in 1990 and run to 2030 without onerous changes in conditions—and wants that certainty in a society that keeps changing its mind and changing its values and that reserves the right to throw the rascals out every two years. Such certainty cannot comfortably coexist with due process and democracy in a labile society, and investors seeking low risk should build short-lead-time, low-impact, understandable—in short, low-inertia—technologies that can adapt to rapidly changing political, economic, and technical circumstances at home and abroad.

Geopolitics

An explosion of interest and activity in soft technologies confirms their proven potential as a powerful tool for Third and Fourth World development as well as for First and Second World redevelopment (56, 145–161). "Light-capital" (162), "inequity-reducing" (25, 92) technologies can adapt locally abundant materials and skills, to meet basic human needs such as cooking, heating, lighting, and pumping, while helping with such fundamental problems as rural emigration, high preferred family size, oil dependence, and firewood shortage (163). Such perceptions are rapidly leading to a redirection of program both for foreign aid and for internal development (164–168), reflected in the mandate of the US Agency for International Development and in the policy of all United Nations organs except the International Atomic Energy Agency.

Arguments are also rapidly gaining ground in the arms-control community that soft energy paths, particularly in the United States, offer a strong political lever to promote a world psychological climate of denuclearization, in which it comes to be viewed as a mark of national immaturity to have or want reactors or bombs. In this view (2), a consistent, synergistic package of policies for civil denuclearization (already becoming a fait accompli (8)), promotion of soft energy paths at home and abroad, and linkage of these actions with work on the slower task of strategic arms reduction would be likely to remove most of the incentives and the political and technical means of nuclear proliferation. While this conclusion rests on a controversial set of political judgments, the proposal appears more consistent and likely to work than its alternatives and is withstanding professional scrutiny well.

THE DEBATE OVER SOFT ENERGY PATHS

An extensive compendium (5) contains all known published critiques (up to November 1977) of the orgiinal soft-path thesis (1)—by 30 individuals and groups—together with full responses and useful supplementary matter. This record shows that most of the critiques reflect straightforward misreadings, limited scholarship, or failure to consult cited references. These weaknesses may be partly due to the high density of the prose (1), its explicit but often unrecognized separation of personal preferences from analytic assumptions, and its tendency to mix traditional engineering and economic perspectives with less familiar ones such as geopolitics and political economy. Some critiques, however, reflect different judgments about how far institutional barriers can or will be overcome, or how far a few working examples of an innovation prove its feasibility. Such differences may reflect temperamental splits between physicists and engineers or between Jeffersonians and Hamiltonians.

The published colloquy supports three broad and disquieting observations. First, intellectual asymmetry (2)—applying different tests of costs, rates, impacts, and feasibility to different technologies—remains prevasive. Second, the technical community seems divided into people who can appreciate elegantly simple devices, achieving impressive effects with a great economy of means, and people, (or more commonly, bureaucracies) that can get excited only about devices that are big, electrified, and full of exotic materials and techniques. Third, many able technical people are not in touch with the myriad of exciting soft-technology developments at the grassroots, and often do not even realize they exist. There are two virtually dichotomous networks of energy researchers, separated by deep gulfs with regard to communication, style, temperament, confidence, and respect. Profound ignorance of what people are doing on the other network is often unrecognized and thus no effort is made to counter the ignorance. If professional discourse is to start from an equal base of knowledge, soft technology skeptics in particular should inform themselves at first hand about the extraordinary range of practical (and impractical but interesting) devices now being built around the world. A nascent literature of appropriate technologies, especially simple ones, offers at least initial points of access (2, 7, 27, 50–52, 56, 62–65, 69, 73, 75, 91, 110, 145–168). Studies of or related to soft energy paths, at varying levels of detail, are now under way in over 15 countries (11, 169) and several regions. In early 1978, subnational studies were also under way in about 10 US states, including a major effort in California (4), and in several Canadian provinces. A small secretariat [21] provides access to all this work. More numerous, explicit, and documented studies are needed, and will be useful both in the regions studied and in others.

RESEARCH ISSUES

A representative sampling of outstanding research issues might include:

1. Systems integration: interation between energy-efficient building design and solar heating system design; scope for passive and hybrid solar retrofits; solar total energy systems; neighborhood solar systems and their transition from fossil-fueled district heating; grid stability and control with dispersed and intermittent sources; effect of materials policy and agricultural and water policies on quantity and quality of energy needed; integration of biomass collection with present crop/forestry collection and with various distribution systems.
2. Deployment rates and logistics: comparative deployment rates; rate sensitivity to removal of particular barriers (4, 170), singly or in combination; interface with tax policy (171) at all levels; rate-limiting steps; numercial details of the transition; institutional lessons from abroad.
3. Technologies: applications of cheap photovoltaics; solar heat engines; nonelectric wind systems; nonnuclear retrofits of nuclear plants; combined heat-power-pyrolysis plants; disaggregated applications of solar process heat; pyrolytic retrofits of pulp mills and other facilities; solar-assisted and enzymatic bioconversion; environmental effects of biomass residue harvesting; collection methods; interface with agricultural reform; passive and hybrid solar heating and cooling (172); seasonal heat storage refinements.
4. Data base and fundamental analysis: long-term welfare measures and economic prospects; long-term macroeconomic consistency (e.g. more self reliance in energy implications of long-term materials, agricultural, and forestry policy; comparative whole-system costs; scale issues; and, above all, thermodynamic and scale spectra of end-use structure and their correlations.

CONCLUSIONS

The thermodynamic and scale structure of end use is the essential technical starting point, and the political structure of energy-using society is the essential paratechnical starting point, for a sound energy policy. These approaches lead naturally to emphasis on the sustainable direct supply and efficient use of heat for buildings and processes and of liquid fuels for transportation, not on further central electrification. To this end, a wide range of relatively simple-to-use renewable energy sources matched in scale and in energy quality to our range of end-use needs is now available at attractive marginal costs. Such soft technologies appear able to make a prompt and major contribution to energy supply (173) compared to alternative investments in central-electric systems, synfuel plants, and other centralized devices to convert depletable fuels to premium energy forms. The former technologies appear superior to the latter in costs, rates, geopolitical implications (including nuclear proliferation), and domestic sociopolitical implications (perhaps the key policy determinant). Soft technologies are therefore starting to be studied in many countries, and increasingly used in practice, to construct smooth transitions (over 50 years or so) to virtually complete reliance on appropriate renewable sources, meanwhile using fossil fuels far more efficiently and cleanly in transitional systems adaptable to soft sources as they are installed. Elaboration and refinement of these analyses, though unlikely to change the conclusions, is necessary, and offers exciting technical challenges. Implementation will be even more interesting.

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